CHAPTER SEVEN

PAVEMENT-MARKING MATERIALS

Environmental regulations have reduced the acceptable levels of volatile organic compound (VOC) content for pavement markings. The regulations and the changes brought to the types of marking materials used are discussed in this chapter. The types of longitudinal markings, pavement markers, and word and symbol markings used by state, province, county, and city agencies are described. Transportation agencies are seeking cost-effective materials that maintain acceptable levels of retroreflectivity. The service lives of marking materials are discussed and typical costs are presented. Service lives and typical costs were used to develop the life-cycle costs of longitudinal pavement markings. The costs of traffic delay during striping operations and retroreflectivity measurements are presented along with an example showing the effects on life-cycle cost. Descriptions of other materials that have the potential for improving nighttime visibility and safety are also presented.

Pavement and curb markings are commonly placed by using paint or thermoplastic; however, other suitable marking materials, including raised pavement markers and colored pavements are also used [*MUTCD 2000* (2000)]. The materials used for markings should provide the specified color throughout their useful life. Consideration should be given to selecting marking materials that minimize tripping or loss of traction for pedestrians and bicyclists.

ENVIRONMENTAL CONSIDERATIONS

Selection of pavement-marking materials is usually done on the basis of engineering performance. The selection process becomes more complicated because of the legal requirement on the permitted VOC content. Some marking systems contain volatile compounds classified as hazardous air pollutants, which are expected to be regulated in the future (Andrady and Crowther 1998).

EPA Regulations on Pavement-Marking Practice

A 1994 FHWA memorandum describes the impact of an EPA regulation on application of various marking materials (Cirillo et al. 1994). The EPA, through a regulation negotiation process, issued an Architectural and Industrial Maintenance (AIM) Coating Rule that significantly reduces the allowable VOC content of highway delineation paints (Code of Federal Regulations 1999). All products manufactured after January 1, 1996, must comply with the new regulation.

A VOC is defined as any organic compound that participates in atmospheric photochemical reactions. That is, any organic compound other than those which the EPA designates as having negligible photochemical reactivity. For a list of compounds that the EPA has designated as having negligible photochemical reactivity, also referred to as exempt compounds, refer to 40 CFR 51.100(s).

The EPA rule is structured with the goal of reducing AIM-coating VOC emissions by 40% by the year 2004, based on the total VOC content of 1990's production (Cirillo et al. 1994). The VOC limits established for pavement-marking materials are shown in Table 29.

TABLE 29
MAXIMUM PERMITTED VOC CONTENT FOR MARKING MATERIALS

	VOC Content	
Year	g/L	lb/gal
2000	150	1.25
2004	100	0.83

Notes: VOC = volatile organic compound; 1 lb = 453.6 g; 1 gal = 3.79 L.
(*Source*: Cirillo et al. 1994.)

A rule provision is possible that would allow for the use of higher VOC materials if seasonal conditions dictate. Table 30 depicts nominal VOC contents of the pavement-marking materials in use in 1994. Solvent-borne paint and primer/sealer exceed EPA VOC limits.

TABLE 30
NOMINAL VOC CONTENT OF PAVEMENT-MARKING MATERIALS IN 1994

	VOC Content	
Marking Material	g/L	lb/gal
Solvent-borne	450+	3.75
Waterborne	150–	1.25
Epoxy resin	0	0
Thermoplastic	0	0
Primer/sealer	350+	2.92
Polyester resin[a]	135–	1.13

Notes: VOC = volatile organic compound; 1 lb = 453.6 g; 1 gal = 3.79 L.
[a]Calculated from formula, not by analysis.
(*Source*: Cirillo et al. 1994.)

Conventional Solvent Paint Use Between the Years 1995 and 2000

Transportation agencies are adopting new policies and practices regarding conventional solvent-borne paint because of the 150 g/L (1.25 lb/gal) EPA VOC regulatory requirement. Andrady (1997B) discusses the properties of solvent paint, reporting on the amount of solvent paint used by state transportation agencies and the District of Columbia in 1995. The results of the year 2000 survey of transportation agencies using conventional solvent-borne paint done for this synthesis were compared with the results of the 1995 survey.

All 50 states and the District of Columbia used solvent paint in 1995. In 2000, 23 states (46%) no longer used solvent paint, 13 states (26%) used solvent paint, and for 14 states (28%) it is unknown whether solvent paint was used.

All five Canadian provinces surveyed reported that solvent paint was the primary marking material in 2000, although other materials are used for special small-scale applications. Four of the five counties and four of the five cities surveyed did not use solvent paint in 2000. Although the use of pavement-marking materials with a VOC level above 150 g/L (1.25 lb/gal) is not prohibited, transportation agencies are adopting policies that reduce the levels of environmental pollutants.

Assessing Engineering and Environmental Performance

The factors often considered when selecting a pavement-marking material include retroreflectivity, durability, and life-cycle cost. Other factors such as the ease of use, the availability of reliable contractors, or even previous experience with different marking systems can also influence the selection. The selection process becomes more complicated because the VOC content limit of 150 g/L (1.25 lb/gal) has to be met. Most engineers have little or no experience in selecting environmentally compatible marking materials (Andrady 1997B; Andrady and Crowther 1998). A decision-making methodology, known as PAMAS (Pavement Marking Assessment System), considers engineering and environmental goals in selecting a marking material (Andrady 1997A, 1997B; Andrady and Crowther 1998). The four engineering performance goals are high visibility, high durability, convenience, and low cost. The two environmental performance goals are low VOC level and health and safety considerations.

The PAMAS methodology can evaluate solvent-borne paints, waterborne paints, epoxy, thermoplastics, polyester, and preformed tape products. Empirical parameters, historical data, and cost information are used in the evaluation. Performance can be assessed manually (Andrady 1997A) or through a software program that can be downloaded from the NCHRP website under Project 4-22 (Andrady 1997B).

TYPES OF PAVEMENT MARKINGS, SERVICE LIFE, COST, AND LIFE-CYCLE COST

The types of long-term pavement markings used by transportation agencies include longitudinal markings, pavement markers, and word and symbol markings. Sixteen types of longitudinal marking materials are used, of which 9 are commonly used, others are used to a lesser extent, and some are in an experimental stage of implementation. The definitions of common marking materials are presented at the end of the report. The service lives of these materials, which vary by color of material and type of pavement surface, is described. Materials are applied at different thicknesses using various bead types, which are applied at different rates. The material and glass bead combinations are compared with FHWA specifications. The types of longitudinal markings, pavement markers, and word and symbol markings used and the costs to obtain and apply them are presented here.

Marking materials have different service lives and costs. The cost of a material combined with its service life is used to develop a life-cycle cost. The life-cycle cost to obtain and apply materials is useful to agencies when selecting materials and budgeting pavement marking programs. Current life-cycle costs of longitudinal marking materials were developed using material costs provided by state agencies and service lives of materials applied on state highways obtained from research results.

Types of Pavement Markings

Table 31 shows the three types of pavement markings (longitudinal, pavement markers, and word and symbol markings) used by the four types of agencies and the numbers of agencies using the various materials. There are 16 types of longitudinal markings, 4 types of pavement markers, and 2 types of word and symbol markings in use.

Longitudinal Pavement Markings

Table 31 lists the longitudinal marking materials used in descending order. Of the 16 types of materials being used, waterborne paint is the most common and is used by 40 of the responding agencies (78%), followed by thermoplastic, which is used by 35 of the agencies (69%). The table shows that state agencies use the greatest variety of markings, followed by counties, cities, and Canadian provinces. The provinces use conventional solvent paint almost exclusively for longitudinal markings, except for small, special jobs where durable materials are used.

TABLE 31
MARKING MATERIALS USED ON THE AGENCY SYSTEM OF ROADS

Types of Markings	Transportation Agencies Reporting Using the Marking Material									
	Total (51)[a]	%[b]	State (37)[a]	%[b]	Canadian (5)[a]	%[b]	County (5)[a]	%[b]	City (4)[a]	%[b]
Longitudinal Markings										
Waterborne paint	40	78	33	89			5	100	2	50
Thermoplastic	35	69	30	81			3	60	2	50
Preformed tape—flat	22	43	19	51			2	40	1	25
Preformed tape—profiled	21	41	20	54					1	25
Epoxy	20	39	19	51			1	20		
Conventional solvent paint	20	39	13	35	5	100	1	20	1	25
Methyl methacrylate	10	20	9	24			1	20		
Thermoplastic—profiled	9	18	9	24						
Polyester	5	10	5	14						
Other	8	16	7	19			1	20		
Other										
Polyurea	2	4	2	5						
Cold applied plastic	1	2	1	3						
Experimental	1	2	1	3						
Green lite powder	1	2	1	3						
Polyester—profiled	1	2	1	3						
Tape removable	1	2	1	3						
HD-21	1	2					1	20		
Pavement Markers										
Raised retroreflective	16	31	14	38					2	50
Recessed retroreflective	4	8	4	11						
Snowplowable retroreflective	16	31	14	38			2	40		
Nonretroreflective	5	10	4	11					1	25
Word and Symbol Markings										
Preformed	34	67	26	70	1	20	4	80	3	75
Striped on site	33	65	25	68	2	40	4	80	2	50

[a]Number of transportation agencies responding to the survey.
[b]Percentage of the responding agencies that reported using the marking material; e.g., 78% (40/51) use waterborne paint.

TABLE 32
STATE AGENCY MILEAGE OF LONGITUDINAL MARKING MATERIALS BY TYPE OF PAVEMENT SURFACE

Longitudinal Marking Material	Centerline Mileage of Material by Type of Pavement Surface						
	N[a]	Total (mi)	%	AC (mi)	%	PCC (mi)	%
Waterborne paint	15	109,058	59.9	102,832	61.9	6,225	39.1
Thermoplastic	13	41,365	22.7	35,087	21.1	6,278	39.4
Conventional solvent paint	6	11,755	6.5	11,578	7.0	178	1.1
Polyester	3	6,857	3.8	6,854	4.1	3	0.0
Epoxy	7	4,877	2.7	4,364	2.6	514	3.2
Preformed tape—flat	7	3,459	1.9	1,952	1.2	1,506	9.5
Thermoplastic—profiled	6	3,383	1.9	2,800	1.7	583	3.7
Preformed tape—profiled	8	1,087	0.6	529	0.3	558	3.5
Methyl methacrylate	2	174	0.1	90	0.1	84	0.5
Total		182,015	100.0	166,087	100.0	15,929	100.0

Note: 1 mi = 1.61 km.
[a]Number of state agencies reporting percentage of material used, percentage of material applied on asphaltic concrete (AC) and portland cement concrete (PCC) pavements, and centerline mileage of AC and PCC pavements.

Longitudinal Pavement Markings by Type of Pavement Surface

Table 32 shows the longitudinal markings used by state agencies and the respective mileage of these materials by pavement type. The materials are listed in descending order according to the total mileage striped with the respective materials. Waterborne paint is striped on almost 60% of the total mileage, and thermoplastic is striped on almost 23% of the total mileage. Almost 62% of AC pavement is striped with waterborne paint, whereas 39% of PCC pavement is striped with waterborne paint. Relatively, a greater percentage of waterborne paint is striped on AC pavement than on PCC pavement. The opposite is true for thermoplastic, where a greater relative percentage is striped on PCC than on AC pavement. Polyester is used much more on AC relative to PCC pavement.

Material Application Rates and Bead Types

The construction requirements for pavement and air temperature, material application thickness, type of glass bead, and bead application rates, described in FP-96, were summarized in Table 23 in chapter 6. Surveyed agencies provided material application rates, applied thicknesses, and bead types. The bead types used by agencies closely conform to the FP-96 specifications. Agencies initially start with the requirements of FP-96 for application thickness and rates and then make slight modifications for local conditions. Modifications to specifications are determined through in-house evaluations or through test programs such as NTPEP where the variations are evaluated. The variations in specifications of individual agencies show that there are no universally accepted sets of practices concerning either material application thickness or bead application rates.

The variation in specifications makes it difficult to determine which specification produces the longest service life. The FHWA researched pavement markings applied in 19 states (Migletz et al. 2000 unpublished data). Although the basic types of materials were the same; that is, thermoplastic, epoxy, etc., the composition of the materials, bead mix, applications rates, manufacturers, etc., varied. The research concluded that there were substantial site-to-site and state-to-state variations in the estimated service lives of longitudinal pavement markings. Many issues of potential interest to agencies, such as varying bead sizes, could not be addressed because of the variation in agency specifications.

Pavement Markers

Guidelines for RRPMs and their application are presented in the MUTCD [*MUTCD 2000* (2000)]. The *Roadway Delineation Practices Handbook* discusses adhesives and presents example application diagrams (Migletz et al. 1994). Table 31 shows the retroreflective raised, recessed retroreflective, snowplowable retroreflective, and nonretroreflective pavement markers and the number of agencies using them. Only state agencies reported using the four types of markers. Canadian provinces did not report using any pavement markers. Approximately one-third (31%) of the agencies reported using both raised and snowplowable retroreflective markers.

Caltrans reported having trouble keeping RRPMs on the pavement in locations with high-traffic volumes and in weaving areas, especially where there is a large percentage of truck traffic. There are no general pavement-related problems except in the desert, where pavement temperature reaches 82ºC (180ºF) during the summer. The mechanical bonding strength is inversely proportional to temperature. The road surface is softened and the RRPMs are pressed into the asphalt or concrete, which eliminates the rumble effect. The white RRPM turns from white to brown from ultraviolet rays and heat from sunlight, rubber tires, and vehicle exhaust. During the rainy season, substantial amounts of water help clean the road and the RRPMs.

Adhesive Specified for Raised Pavement Markers

Agencies specify bituminous, epoxy, and rubber butyl pads as the adhesives for attaching RRPMs to the pavement. There is no clear consensus of practice with regard to adhesive and type of pavement. All three types of adhesive are used on AC and PCC pavements. Bituminous is specified only for AC pavements by three agencies, whereas epoxy is specified only for PCC pavements by four agencies. Six agencies use only bituminous, 11 agencies use only epoxy, and 2 agencies use only rubber butyl pads. Eight agencies follow manufacturer recommendations for the type of adhesives including the Nebraska Department of Roads, which uses only adhesives recommended by the RRPM manufacturer and does not specify any type of adhesive. As with the results of the agency survey, the results of the manufacturer survey are mixed with regard to type of adhesive used.

Approximately 96% of the adhesive used by Caltrans is bituminous. Epoxy adhesive is no longer used because it is a hazardous waste and gives off a bad odor. Epoxy takes approximately 2 to 3 h to settle and dry and costs three times more than bituminous adhesive.

Word and Symbol Pavement Markings

Table 31 shows the two types of word and symbol markings being used and the number of agencies using them. Approximately two-thirds of the agencies reported using both preformed and striped-on-site word and symbol markings, which are about equally used. Preformed word and symbol markings are made of plastic and are attached to the pavement with an adhesive or bonded to the pavement surface by heating with a torch. Thermoplastic is the primary material for word and symbol markings that are striped on site, although conventional solvent paint is used in Canada.

Service Life

Longitudinal and word and symbol markings can reach the end of service life either because of bead loss resulting in poor retroreflectivity, loss of the base material because of chipping and abrasion, or color change or the loss of contrast of the base material of the marking. Daytime and nighttime visibility are closely related because as a marking is chipped or abraded by traffic action there typically is not only loss of marking material, which decreases the daytime visibility of the marking, but also loss of beads, which reduces the nighttime retroreflectivity of the marking.

The service life of an RRPM depends on the strength of the bond between the marker and the pavement surface and

TABLE 33
ESTIMATED SERVICE LIFE BY MARKING MATERIAL AND COLOR OF LINE FOR SITES WITHOUT ROADWAY LIGHTING AND RAISED RETROREFLECTIVE PAVEMENT MARKERS

Material	No. of Pavement Marking Lines	Service Life[a] In: CTP (million vehicles)			Service Life[a] In: Elapsed Months			Data for Table 6–13 Alternate: Elapsed Months		
		Ave.	SD	Range	Ave.	SD	Range	Ave.	SD	Range[b]
White Lines										
Waterborne paint	3	3.7	4.0	0.9 – 8.3	10.4	7.3	4.1 – 18.4	10.4	7.3	3.1 – 17.7
Epoxy	18	4.4	4.2	0.4 – 17.0	23.0	17.1	1.0 – 56.0	23.0	17.1	5.9 – 40.1
Methyl methacrylate	7	3.6	4.0	0.6 – 12.0	14.4	7.6	6.8 – 29.3	14.4	7.6	6.8 – 22.0
Methyl methacrylate—profiled	9	8.2	8.5	2.3 – 29.2	21.0	13.4	7.8 – 43.2	21.0	13.4	7.6 – 34.3
Polyester	5	5.5	5.5	1.1 – 15.1	24.7	7.9	14.7 – 34.1	24.7	7.9	16.9 – 32.6
Polyester—profiled	1	10.9	—	10.9 – 10.9	45.9	—	45.9 – 45.9	45.9	—	45.9 – 45.9
Preformed tape—profiled	11	6.2	3.9	1.1 – 12.3	27.4	13.6	11.7 – 60.0	27.4	13.6	13.8 – 41.0
Thermoplastic	19	7.1	7.2	0.6 – 28.8	26.2	14.1	7.4 – 49.7	26.2	14.1	12.1 – 40.3
Thermoplastic—profiled	14	6.7	6.8	1.0 – 25.1	23.8	12.8	4.7 – 55.7	23.8	12.8	11.1 – 36.6
Yellow Lines[c]										
Epoxy	15	6.2	3.3	1.2 – 11.4	34.3	14.6	12.6 – 57.8	34.3	14.6	19.8 – 48.9
Methyl methacrylate	4	3.5	2.9	1.0 – 7.0	16.8	4.2	12.6 – 20.5	16.8	4.2	12.6 – 21.0
Methyl methacrylate—profiled	5	6.3	2.1	4.1 – 9.1	25.0	6.0	18.1 – 32.8	25.0	6.0	19.1 – 31.0
Polyester	2	10.1	1.4	9.1 – 11.1	43.8	5.8	39.7 – 47.9	43.8	5.8	38.0 – 49.6
Polyester—profiled	1	4.7	—	4.7 – 4.7	39.6	—	39.6 – 39.6	39.6	—	39.6 – 39.6
Preformed tape—profiled	7	5.6	3.0	2.3 – 9.7	30.6	11.9	19.6 – 53.4	30.6	11.9	18.7 – 42.5
Thermoplastic	10	5.7	5.2	1.3 – 15.2	27.5	12.1	11.0 – 41.6	27.5	12.1	15.4 – 39.5
Thermoplastic—profiled	8	5.5	3.1	1.9 – 11.4	26.7	10.3	17.8 – 50.7	26.7	10.3	16.4 – 37.0

Notes: 1 mi = 1.61 km; CTP = cumulative traffic passages; SD = standard deviation; ave. = average.
[a]Service life is weighted by the number of pavement marking lines in the three roadway types/speed classifications shown previously in Table 6. (See Migletz et al. 2000 unpublished data, Table 7 for the number of pavement marking lines in each roadway type/speed classification.)
[b]Insufficient data to provide results for yellow waterborne paint.
[c] Range from one standard deviation below to one standard deviation above the mean service life.
(*Source*: Migletz et al. 2000 unpublished data.)

the durability of the reflective element in the RRPM. An RRPM becomes ineffective because of dirt accumulation on the lenses, abrasions, and weathering. The service lives of longitudinal pavement markings and RRPMs are discussed here.

Service Life of Longitudinal Pavement Markings

The service life of a longitudinal pavement marking is the time or number of traffic passages required for its retroreflectivity to decrease from its initial value to a minimum threshold value that indicates that the marking needs to be refurbished or replaced. The threshold values of retroreflectivity used in FHWA research to determine the end of service life are shown in Table 6 in chapter 3.

The marking material, type and color of line, and the type of roadway were the primary factors considered in the development of the relationship between retroreflectivity and the elapsed time since marking installation. The severity of winter climate was assessed, but was not found to have a consistent effect on pavement-marking service life (Migletz et al. 2000 unpublished data). Retroreflectivity measurements were made at 85 study sites in 19 states over a 4-year period from 1994 to 1998 using the Laserlux 30-m (98.4-ft) mobile retroreflectometer (with early geometry as shown in Table 3 in chapter 3) under dry pavement conditions.

Table 33 summarizes the estimated average service lives for pavement markings by material and color of line for both cumulative traffic passages (CTP) and elapsed months (Migletz et al. 2000 unpublished data). The service lives are intended for application to locations at which no RRPMs or roadway lighting are present. The results in the table are a combination of the three roadway types shown in Table 6 in chapter 3 weighted by the number of pavement-marking lines in each roadway type. The table also shows the number of lines (or pairs of similar lines in opposite directions of travel), standard deviation, and range of service lives. Yellow materials have longer service lives than corresponding white materials, because the minimum threshold values used to determine the end of service life for white markings is at least 50% greater than for yellow markings.

The service lives were first calculated in CTP and then converted to elapsed months using Equation 1 (Migletz et al. 2000 unpublished data). CTP gives a more accurate estimation of service life, but elapsed months is easier to understand. It is recommended that service life be calculated in

TABLE 34
ESTIMATED SERVICE LIFE BY MARKING MATERIAL AND COLOR OF LINE FOR SITES WITH ROADWAY LIGHTING AND/OR RAISED RETROREFLECTIVE PAVEMENT MARKERS

Material	No. of Pavement Marking Lines	Service Life[a] In: CTP (million vehicles) Ave.	SD	Range	Elapsed Months Ave.	SD	Range
White Lines							
Waterborne paint	3	12.5	6.6	6.2 – 19.3	41.3	12.7	27.8 – 53.1
Epoxy	26	10.3	6.2	2.0 – 28.7	38.5	25.5	8.1 – 100.6
Methyl methacrylate	9	10.2	7.5	1.9 – 23.4	36.8	19.3	13.0 – 67.9
Methyl methacrylate—profiled	9	53.8	124.0	6.4 – 384.4	84.7	133.8	24.8 – 440.2
Polyester	5	18.0	24.7	2.5 – 61.7	63.9	28.3	38.5 – 110.0
Polyester—profiled	1	13.0	—	13.0 – 13.0	54.4	—	54.4 – 54.4
Preformed tape—profiled	12	13.9	11.5	2.6 – 36.9	45.5	16.3	26.8 – 78.0
Thermoplastic	20	13.6	11.5	1.9 – 44.6	47.7	16.6	22.7 – 76.8
Thermoplastic—profiled	14	11.5	8.5	1.4 – 30.3	41.7	15.0	21.4 – 67.2
Yellow Lines[b]							
Epoxy	17	9.3	5.0	1.9 – 18.7	45.6	19.7	22.6 – 80.1
Methyl methacrylate	5	6.3	4.1	1.8 – 9.9	26.4	8.7	18.5 – 40.6
Methyl methacrylate—profiled	5	8.8	3.0	6.1 – 13.1	34.4	6.3	28.6 – 44.7
Polyester	2	12.9	2.3	11.2 – 14.5	55.5	5.1	51.9 – 59.1
Polyester—profiled	1	5.2	—	5.2 – 5.2	43.6	—	43.6 – 43.6
Preformed tape—profiled	7	7.3	4.9	3.0 – 14.5	37.0	11.4	21.5 – 56.8
Thermoplastic	11	10.7	13.3	2.0 – 48.2	46.0	24.9	24.1 – 103.4
Thermoplastic—profiled	8	7.6	3.9	2.3 – 14.6	36.7	13.1	27.4 – 64.7

Notes: CTP = cumulative traffic passages; 1 mi = 1.61 km.
[a]Service life is weighted by the number of pavement marking lines in the three roadway types/speed classifications shown in Table 6. (See Migletz et al. 2000 unpublished data, Table 8 for the number of pavement marking lines in each roadway type/speed classification.)
[b]Insufficient data to provide results for yellow waterborne paint.

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

CTP and reported in elapsed months. Traffic passages for an edge line were based on the traffic volume in the adjacent lane, whereas for centerlines and edge lines it was based on the sum of traffic volumes for the two adjacent lanes.

$$SL_{\text{Months}} = \frac{SL_{CTP}}{\left[\dfrac{CTP_{\text{Final}}}{Date_{\text{Final}} - Date_{\text{Install}}}\right]\left[\dfrac{365.25\text{ days}}{12\text{ months}}\right]} \qquad (1)$$

where

SL_{Months} = Service life in elapsed months,
SL_{CTP} = Service life in cumulative traffic passages (millions of vehicles),
CTP_{Final} = Cumulative traffic passages (millions of vehicles) at final field measurement date,
$Date_{\text{Final}}$ = Date of final field measurement, and
$Date_{\text{Install}}$ = Installation date of pavement marking.

Table 34 is analogous to Table 33 but presents estimated service lives for pavement markings installed where RRPMs or roadway lighting is present (Migletz et al. 2000 unpublished data). The service lives shown in Table 34 are longer than those shown in Table 33 because lower threshold retroreflectivity values would apply when RRPMs or roadway lighting is present (see Table 6). The results of FHWA research shows that there are substantial variations in service life as indicated by the ranges. The factors that are presumed to contribute to this decrease in pavement-marking retroreflectivity include the passage of time, action of traffic, exposure to ambient weather conditions, snowplow operations, marking material specifications, pavement surface preparation, and quality control at the time when markings are placed (Migletz et al. 2000 unpublished data). Since the FHWA study was done, there have been improvements to marking materials. The service life of a material placed today may be longer than in the period from 1994 to 1996 when the materials studied were installed. The service lives of white marking materials used by VDOT are shown in Table 35 and are longer than the average values of corresponding materials in Table 33. The VDOT service lives of waterborne paint, thermoplastic, and epoxy fall within the ranges in the table, whereas profiled preformed tape exceeds the range in the table (Cottrell and Hanson 2001).

TABLE 35
VIRGINIA DOT SERVICE LIVES OF WHITE MARKING MATERIALS

Material	Service Life (yr)
Waterborne paint	1
Epoxy	3
Polyurea	3
Preformed tape—profiled	6
Thermoplastic	3

(*Source*: Cottrell and Hanson 2001.)

TABLE 36
MEAN PAVEMENT-MARKING SERVICE LIFE IN ELAPSED MONTHS BY COLOR OF MARKING

	Pavement-Marking Service Life in Elapsed Months (sample size) by Roadway Type/Speed		
Pavement Marking Color	Non-freeway ≤40 mph	Non-freeway ≥45 mph	Freeway >55 mph
White	39.0 (6)	33.0 (27)	16.9 (54)
White with RRPMs or lighting	54.0 (6)	54.6 (27)	43.6 (66)
Yellow	39.6 (5)	35.9 (19)	23.4 (28)
Yellow with RRPMs or lighting	50.6 (5)	46.8 (19)	35.9 (32)

Note: 1 mi = 1.61 km.
(*Source:* Migletz et al. 2000 unpublished data, p. 223.)

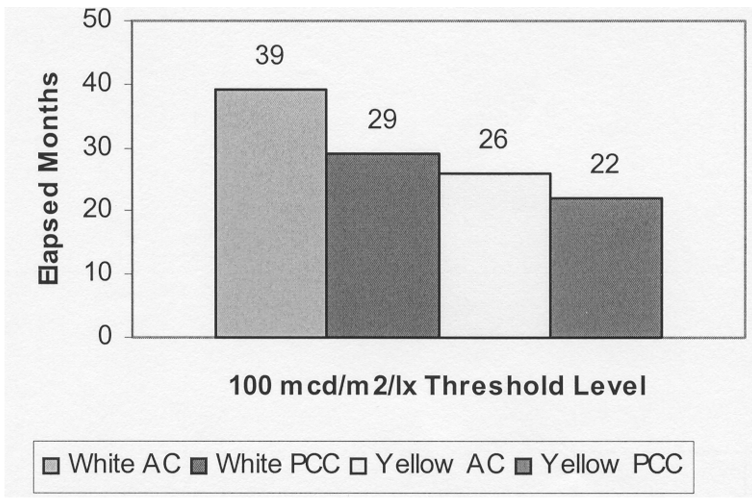


FIGURE 24 Service life in months of durable pavement markings by color of line and type of pavement. [Notes: Excluding waterborne, marking materials are shown in Table 31. Without regard to type of pavement the service life of white lines is 34 months and for yellow lines 24 months. Without regard to color of line the service life of lines on AC pavement is 22 months and 26 months on PCC pavement. Data collected with early Laserlux 30-m (98.4-ft) mobile retroreflectometer (see Table 3)]. (*Source*: Migletz et al. 2000 unpublished data.)

Table 36 summarizes the mean pavement-marking service life in elapsed months in categories of pavement marking color, presence or absence of RRPMs and lighting, roadway type, and speed classification corresponding to the cells used to define the threshold values of retroreflectivity (see Table 6 in chapter 3). The summary gives an indication of the service lives that would be achieved if the FHWA-recommended minimum threshold values were implemented. Table 36 indicates that service lives of pavement markings are likely to be shorter on freeways, where both the threshold values and traffic volumes are higher, than on non-freeways. A system where white and yellow markings reach the end of service life at the same time would be cost-efficient because the markings could be replaced at the same time without wasting excess service life. White and yellow markings in the non-freeway ≤40 mph class have the same service lives (approximately 39 months), whereas white markings in the freeway ≥55 mph class (17 months) have a shorter life than yellow markings (23 months) in the same class.

Service Life of Longitudinal Pavement Markings by Color of Line and Type of Pavement Surface

Figure 24 shows the service life of durable longitudinal pavement markings by color of line and type of pavement surface at a threshold value of 100 mcd/m^2/lux. The data used to develop Table 33 were used to develop this figure, except that waterborne paint was excluded (Migletz et al. 2000 unpublished data). The figure shows the service life in elapsed months from the time that the markings were placed until the threshold level of 100 mcd/m^2/lux was reached. Service lives are presented for white lines on AC pavement, white lines on PCC pavement, yellow lines on AC pavement, and yellow lines on PCC pavement.

The service life of longitudinal pavement markings varies by color of line and type of pavement surface. At a threshold value of 100 mcd/m^2/lux, white lines have a service life of 34 months, which is 42% greater than the 24-month service life of yellow lines. The longer service life of white materials shows a benefit of an all-white system of pavement markings.

Lines on AC pavement have a service life of 33 months, which is 27% greater than the 26-month service life of lines on PCC pavement. The AC pavement surface texture is rougher than PCC, which contributes to the longer service lives on AC pavement.

White lines on AC pavement have a service life that is 34% greater than white lines on PCC pavement. Yellow lines on AC pavement have a service life that is 18% greater than yellow lines on PCC pavement.

White lines on AC pavement have a service life that is 50% greater than yellow lines on AC pavement. White lines on PCC pavement have a service life 22% greater than the service life of yellow lines on PCC pavement.

Service Life of Pavement Markers

The Georgia DOT has an extensive RRPM program where they are used to supplement pavement markings on all types of state highways. It is more cost-effective to use only bituminous adhesive on both pavement types for the 2-year replacement program in most areas of the state, except for the northern counties where they are usually replaced every year because of snow plowing. The Georgia DOT has not reported any problems with RRPMs adhering to the road surface using a bituminous adhesive.

The TTI evaluated the retention time of RRPMs on AC pavement (Tielking and Noel 1989). Retention time is believed to be largely limited by the fatigue strength of the pavement surface. The adhesive material used to bond the markers to the pavement surface can influence the fatigue strength of AC pavement. This is true even though there is very little penetration of the adhesive into the pavement. The fatigue studies show that a more compliant adhesive, for example, bituminous, will give a new AC pavement, the more compliant pavement, a longer fatigue life than a stiffer adhesive such as epoxy. A longer pavement fatigue life means the marker will stay in place for a greater number of tire impacts.

The laboratory studies indicated that for stiffer AC surfaces the advantage of the bituminous adhesive decreased (Tielking and Noel 1989). The advantage of bituminous adhesive also decreased as the force level was increased. The advantage that bituminous adhesive exhibits over epoxy is largely lost for older AC pavement surfaces and for pavements with truck traffic. It was concluded that bituminous adhesive is distinctly superior to epoxy adhesive on new asphalt surfaces. The distinction between bituminous and epoxy adhesive is less pronounced on stiffer (seasoned) pavements.

A Texas DOT study evaluated the retroreflectivity and durability of 17 types of RRPMs on four freeways in the San Antonio area over a 2-year period (Ullman 1994). RRPM retroreflectivity was sampled in the laboratory and then measured in place on the pavement using a hand-held retroreflectometer (different from those used to measure pavement-marking retroreflectivity). Retroreflectivity of a sample of RRPMs removed from the pavement was also measured in the laboratory to compare with field measurements. The one-directional traffic volumes over the 2-year period ranged from 3,300 to 4,500 veh/day at the low-volume site to 58,900 to 63,200 veh/day at the high-volume site, with a truck volume of between 3 and 15%.

Results of nonlinear regression analysis showed that retention of retroreflectivity tends to be most dependent on cumulative vehicle exposure. Many of the RRPMs failed to provide adequate levels of retroreflectivity after as little as 6 months exposure on high-volume freeways (Ullman 1994). The Oregon DOT found that the retroreflectivity of RRPMs may decrease by as much as 70% in 1 year (Hofmann and Dunning 1995). Two types of problems reduced retroreflectivity: retroreflective lenses worn by tire abrasions and retroreflective lenses designed to accommodate tire abrasion that accumulated dirt (Ullman 1994).

The RRPMs were attached to the AC pavements with a bituminous adhesive (Ullman 1994). The rate at which RRPMs became detached from the pavement averaged less than 6%; however, one type of RRPM with a waffle pattern base experienced a much higher loss rate. It appears that the waffle pattern cuts into the adhesive and separates itself from the adhesive and pavement.

The research concluded that the more durable and expensive RRPMs become cost-effective alternatives once AADT levels reach 10,000 veh/day per lane (Ullman 1994). The hand-held retroreflectometer provided an efficient and reasonably accurate estimate of RRPM retroreflectivity throughout the study.

The Texas DOT guidelines for the maintenance and replacement of RRPMs based on a nighttime inspection are presented in Table 37. Regardless of age, a system of RRPMs is considered no longer effective when they become worn and lose retroreflectivity. Special emphasis

TABLE 37
TEXAS DOT GUIDELINES FOR INSPECTING AND REPLACING RETROREFLECTIVE RAISED PAVEMENT MARKERS BASED ON A NIGHTTIME INSPECTION

When to Schedule Retroreflective Raised Pavement Marker System Maintenance Based on a Nighttime Inspection	
Marker Spacing (ft)	Maintenance Should Be Scheduled as Soon as Possible if
80	Fewer than two markers are visible
40	Three or fewer markers are visible
Suggested Replacement Cycle for Retroreflective Raised Pavement Markers	
Roadway (ADT)	Replacement Schedule
>50,000	1 year
≥10,000	2–3 years
<10,000	3–4 years

Notes: ADT = average daily traffic; 1 ft = 0.305 m.
(*Source:* "Maintenance and Replacement of RPMs . . ." 2000.)

TABLE 38
PERCENTAGE OF MARKING MATERIAL MILEAGE AND DOLLARS SPENT BY STATE AGENCIES FOR LONGITUDINAL PAVEMENT MARKINGS

Longitudinal Marking Material	*N*	Total Mileage in 2000 (%)[a]	Total Dollars in 2000 (%)[a]	Total Mileage in 2000 (%)[b]
Waterborne paint	23	58	17	36
Thermoplastic	20	21	35	14
Epoxy	11	6	7	3
Conventional paint	8	5	2	42
Tape-profiled and flat	22	5	26	2
Polyester	5	2	2	3
Thermoplastic—profiled	7	2	7	—[b]
Methyl methacrylate	7	1	5	<1
		100	100	100

Notes: The second, third, and fourth columns were developed from survey data, whereas the fifth column was derived from a 1995 survey of state agencies (Andrady 1997). *N* = number of state agencies providing the annual expenditure for pavement markings, percentage of materials used, and total centerline mileage.
[a]Weighted by the mileage of the materials.
[b]Profiled thermoplastic is included with thermoplastic.

should be placed on maintaining a high-quality RRPM system on Interstate highways.

Maintenance of existing RRPMs before the recommended full-replacement cycle involves the replacement of only those that are missing. It is generally considered practical to maintain RRPMs only at spot locations using butyl rubber adhesive pads or hand-mixed epoxy adhesive. If a roadway has several areas needing new RRPMs it is more practical to replace them. Guidelines for replacing an entire system of RRPMs are also shown in Table 37.

Cost to Obtain and Apply Pavement Markings

The surveyed agencies provided the costs to obtain, place, and repair pavement markings, and included costs for longitudinal markings, pavement markers, and word and symbol markings as discussed here.

Pavement-Marking Expenditure and Mileage

Table 38 presents materials used by state agencies for longitudinal lines and the dollars spent on these materials. The table shows the relative mileage and costs for eight different materials.

Agencies provided the amount of each material used as a percentage of all the longitudinal markings and the unit cost of the materials. In addition to the annual expenditure, the mileage of each material and the amount of money spent for each material were calculated and converted to the percentages shown in the table.

Study survey data show that waterborne paint is the most widely used material followed by thermoplastic (extruded and sprayed). The mileage of other materials is considerably lower. Although more than twice as many miles of waterborne paint are used than thermoplastic, twice as much is spent on thermoplastic than on waterborne paint. The epoxy and polyester mileage is about in the same proportion as the money spent on them. The tape products and methyl methacrylate have relatively high cost-to-mileage ratios.

By comparing the percentage of year 2000 material mileage with that from 1995, the change in the amount of materials used over the period can be determined. Use of waterborne paint has increased by 22%, whereas the use of

TABLE 39
COST OF LONGITUDINAL PAVEMENT MARKINGS APPLIED BY AGENCIES AND CONTRACTORS

Transportation Agency and Longitudinal Marking Material	Cost of Agency-Applied Pavement Markings			Cost of Contractor-Applied Pavement Markings			Combined Cost of Pavement Markings		
	N	Typical Cost ($/linear-ft)	Range ($/linear-ft)	*N*	Typical Cost ($/linear-ft)	Range ($/linear-ft)	*N*	Typical Cost ($/linear-ft)	Range ($/linear-ft)
State									
Waterborne paint	24	0.05	0.02–0.20	21	0.08	0.02–0.18	45	0.06	0.02–0.20
Conventional solvent paint	6	0.05	0.04–0.08	8	0.08	0.02–0.15	14	0.07	0.02–0.15
Epoxy	1	0.08	0.08–0.08	14	0.27	0.09–0.65	15	0.26	0.08–0.65
Methyl methacrylate	1	0.70	0.70–0.70	4	1.35	1.00–1.53	5	1.22	0.70–1.53
Methyl methacrylate—inlayed	0			1	4.00	4.00–4.00	1	4.00	4.00–4.00
Methyl methacrylate—profiled	0			2	1.44	1.12–1.75	2	1.44	1.12–1.75
Polyester	0			5	0.13	0.05–0.30	5	0.13	0.05–0.30
Polyurea	0			1	0.90	0.90–0.90	1	0.90	0.90–0.90
Preformed tape—flat	4	0.92	0.12–1.50	11	1.59	1.01–2.00	15	1.41	0.12–2.00
Preformed tape—profiled	1	2.10	2.10–2.10	15	2.34	1.50–3.10	16	2.33	1.50–3.10
Thermoplastic	3	0.14	0.08–0.25	20	0.34	0.10–0.85	23	0.32	0.08–0.85
Thermoplastic—profiled	1	0.35	0.35–0.35	7	0.95	0.55–1.30	8	0.87	0.35–1.30
Thermoplastic—sprayable	0			1	0.15	0.15–0.15	1	0.15	0.15–0.15
Canadian[a]									
Conventional solvent paint	3	0.02	0.01–0.03	3	0.03	0.03–0.03	6	0.02	0.01–0.03
County									
Waterborne paint	2	0.05	0.03–0.06	3	0.09	0.04–0.15	5	0.07	0.03–0.15
Epoxy	0			1	0.33	0.33–0.33	1	0.33	0.33–0.33
HD-21	0			1	0.18	0.18–0.18	1	0.18	0.18–0.18
Methyl methacrylate	0			1	2.00	2.00–2.00	1	2.00	2.00–2.00
Thermoplastic	0			2	0.79	0.45–1.13	2	0.79	0.45–1.13
City									
Waterborne paint	1	0.04	0.04–0.04	1	0.09	0.09–0.09	2	0.06	0.04–0.09
Conventional solvent paint	1	0.12	0.12–0.12	1	0.25	0.25–0.25	2	0.19	0.12–0.25
Preformed tape—flat	1	0.64	0.64–0.64	0			1	0.64	0.64–0.64
Preformed tape—profiled	0			1	0.85	0.85–0.85	1	0.85	0.85–0.85
Thermoplastic	0			2	0.40	0.40–0.40	2	0.40	0.40–0.40

Notes: Transportation agencies responding to the survey; 37 state, 5 province and territory, 5 county, and 4 city. *N* = number of survey responses; 1 ft = 0.35 m.
[a]Canadian province and territory costs are in $U.S., converted at the exchange rate of $1.00 U.S. = $1.5076 Canadian (March 29, 2001).

conventional solvent paint has decreased by 37%. The use of polyester showed a slight decrease from 1995. Environmental regulations have generated the shift away from conventional paint, and some of this shift has been toward the increased use of durable materials.

Cost to Obtain and Apply Longitudinal Pavement Markings

Agencies provided the unit cost for obtaining and placing each of the materials used on the agency system of highways for markings applied by agency forces and contractors. The costs were provided for longitudinal markings, pavement markers, and word and symbol markings. Table 39 presents the costs of longitudinal markings, which are summarized by the type of material for the four types of agencies—state, province and territory, county, and city. The unit costs and the range of costs of each material are provided for markings applied by both agency forces and contractors. For example, the typical cost for waterborne paint applied by state agencies is $0.16/linear-m ($0.05/linear-ft) and ranges from $0.07 to $0.66/linear-m ($0.02 to $0.20/linear-ft).

The total cost of pavement markings is the weighted typical cost that combines the costs of markings applied by agencies and contractors. This provides a better picture of what it costs agencies to have the various materials applied. The combined costs for state agencies are used in subsequent analyses to determine the life-cycle costs of the various materials.

Table 39 also shows the numbers of agencies applying the materials with agency personnel and contractors. For example, 24 states reported applying waterborne paint with agency personnel and 21 with contractors. Epoxy requires

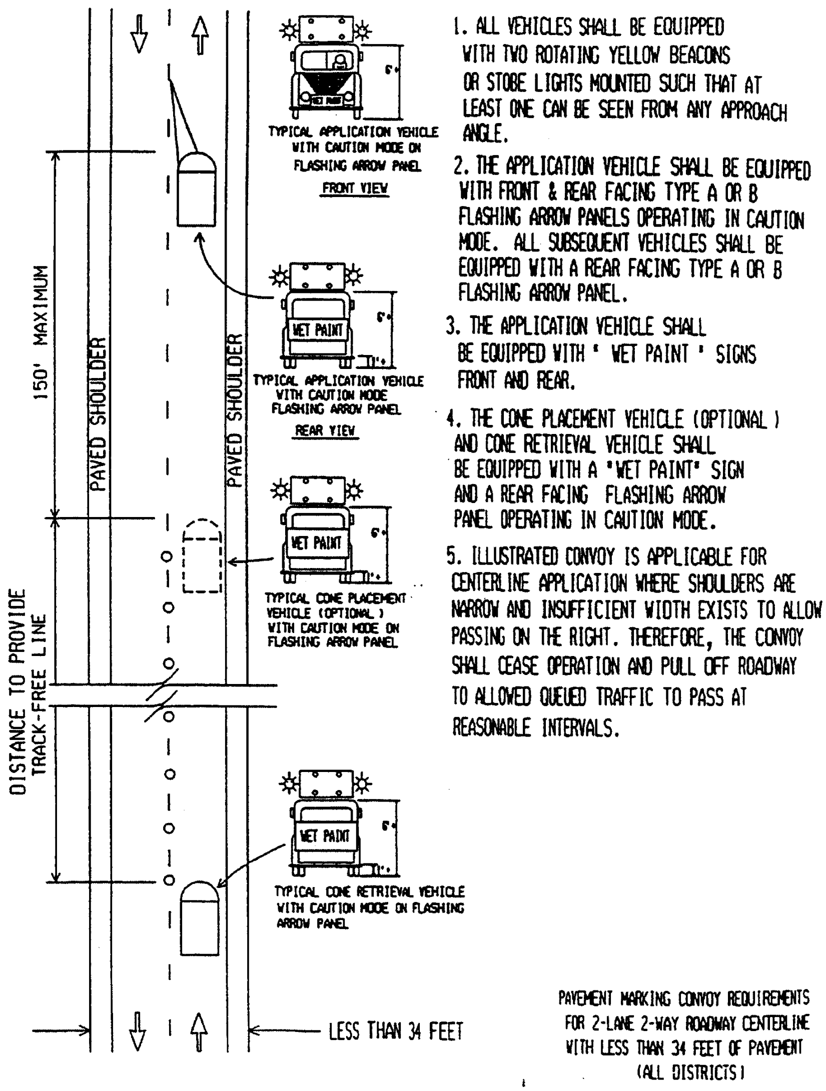


FIGURE 25 Pavement marking convoy requirements for two-lane, two-way roadway centerline. (*Source*: Michigan DOT.)

special equipment to apply. Agency personnel apply epoxy in just one state, whereas contractors apply epoxy in 14 states. Many agencies do not have the funds to purchase the special equipment needed to apply some of the durable materials and therefore rely on contractors who have the equipment and skilled personnel for these specialized applications.

Cost of Traffic Delay

Delay to traffic when roads are being marked under traffic is another cost to be added to that for obtaining and placing markings. Traffic is delayed because a striping convoy moves much more slowly than normal traffic. In addition, a striping convoy will be spread out and at times and under some circumstances, for example, on a two-lane highway, traffic may not be able to pass. VDOT determined the added cost of traffic congestion and delay by determining traffic delay and assigning a cost for the delay (Cottrell and Hanson 2001).

Figure 25 shows a typical application diagram for a mobile striping operation. This diagram shows a convoy consisting of the application vehicle (striper) and one or two other vehicles. The other vehicles provide advance warning and safety for the striper and place and retrieve traffic cones. The advance spacing of the cone retrieval vehicle is based on the no-track time of the material; the longer the drying time, the longer the spacing. For example, when applying waterborne paint with a no-track time of 60 s (“Paint Pavement Marking Material” 2000) at a striping speed of 11 km/h (7 mph) (Cottrell and Hanson 2001), the advance spacing is 188 m (616 ft). At times, the spacing will be even greater, because the advance vehicle has to provide stopping-sight distance for the approaching

TABLE 40
ESTIMATED COST OF TRAFFIC DELAY FROM STRIPING OPERATIONS ON VIRGINIA HIGHWAYS

Scenario	Delay (veh-h/mi)	Delay Cost ($/mi/pass)	Total Delay Cost ($/mi)[a]
Two lanes, 400 vph	3.94	64	193
Two lanes, 400 vph (0.5 mi)	2.3	38	113
Two lanes, 1000 vph	16.3	267	800
Two lanes, 1000 vph (0.5 mi)	13.7	224	673
Two lanes, 2000 vph[b]	35	573	1718
Four lanes, 800 vph[b]	0.05	1	2
Four lanes, 2000 vph	1.6	26	52
Four lanes, 4000 vph	22.5	368	736
Six lanes, 1500 vph[b]	0	0	0
Six lanes, 3000 vph	0.6	10	29
Six lanes, 6000 vph	30.3	496	1488

Note: 1 mi = 1.6 km.
[a]A two-lane road is striped in three passes; one side of a four-lane road is striped in two passes; and one side of a six-lane road is striped in three passes.
[b]Not used in further analyses.
(*Source:* Cottrell and Hanson 2001.)

traffic. At 88.5 km/h (55 mph), at least 137 m (450 ft) of stopping-sight distance is required (*A Policy on Geometric Design* . . . Table III-I 1990). Traffic delay resulting from marking installation was estimated by means of computer simulation (Cottrell and Hanson 2001). Simulations were done for two-, four-, and six-lane road sections for a variety of traffic volume conditions rated as low, medium, and high. A 1.6-km (1-mi) section was used with the striper in the right lane. The speed of the mobile operation was assumed to be 11 km/h (7 mph). It was also assumed that 2% of the traffic consisted of trucks, a figure that may be too low. However, for relative comparison purposes between marking materials, the simulation and assumptions were adequate. The intent was to obtain the relative estimate of the impact of delay on the cost of pavement marking installation as the traffic volume and roadway type were varied.

The vehicle-hours (veh/h) of delay were converted to a cost for delay. The estimated 1999 value of 1 h of travel was $16.10 and $29.42 per hour, respectively, for cars and trucks (Cottrell and Hanson 2001). A weighted average of 1 h of travel was multiplied by the vehicle-hours of delay to obtain the cost of delay for pavement markings.

The delay, delay cost per pass, and total delay cost for marking a 1.6-km (1-mi) section of roadway are shown in Table 40 (Cottrell and Hanson 2001). The number of trips (passes) a striper makes through a road section to complete the marking installation was based on actual practice. Three passes were used on a two-lane road, three passes were used on one side of a six-lane road, and two passes were used on one side of a four-lane road to minimize the number of vehicles crossing and tracking the markings before they dry. For example, on a two-lane road, one pass is made for each edge line and the centerline.

Table 40 shows that three scenarios were not used in further analyses. The two-lane, 2,000 veh/h scenario resulted in a very high, unrealistic level of delay. The low-volume scenarios for four- and six-lane roads resulted in very little, if any, delay. In practice, if vehicles are queuing up behind the striper, the marking crew will pull over before 1.6 km (1 mi) is marked to release the queue and reduce delay. Therefore, two scenarios on two-lane roads with 0.8-km (0.5-mi) sections were added.

Although the cost of delay is a major reason for making durable markings more cost-effective on higher-volume roads, it is less of a factor on the highest-volume roads because the pavement markings are usually installed at night to minimize traffic delay, although the traffic volume is still at a medium level at night (Cottrell and Hanson 2001). Based on VDOT experience, the service life of waterborne paint is decreased where traffic volumes are highest. Therefore, cost-effective durable markings are appropriate at higher-volume sites.

Cost of Measuring Retroreflectivity

The cost of measuring the retroreflectivity can also be incorporated into the striping and life-cycle costs. The West Virginia DOT summarized state costs for the years 1998 through 2000 for measuring retroreflectivity using a 30-m (98.4-ft) mobile retroreflectometer. The costs shown in Table 41 are based on unit costs for measuring retroreflectivity at $0.016/m ($0.005/ft) and for mobilization at $0.007/m ($0.002/ft) (Kenney 2001).

Measurement of retroreflectivity can be done on a statistical sampling basis, with the cost per mile measured spread over the total mileage striped. Sampling provides a reliable estimate of retroreflectivity and helps minimize cost. In Michigan, for each route where retroreflectivity was sampled, the state sampled 10% (Migletz et al. 1999 unpublished report). The entire length of the route across the state was sampled in 3.22-km (2-mi) increments.

TABLE 41
WEST VIRGINIA DOT MOBILE RETROREFLECTIVITY MEASUREMENT COSTS

Measure Retroreflectivity [$/km ($/mi)]	Mobilization [$/km ($/mi)]	Total [$/km ($/mi)]
16.40 (26.40)	6.56 (10.56)	22.96 (36.96)

Note: 1 mi = 1.61 km.
(*Source*: Kenney 2001.)

Cost to Obtain and Apply Pavement Markers

Table 42 presents the reported cost to obtain and apply pavement markers on transportation agency highway systems. The table is in the same format as Table 39, and presents costs for agency- and contractor-applied pavement markers, as well as the combined cost. Table 31 shows that raised and snowplowable pavement markers are the most commonly used, but that the combined cost data shows, that for state agencies, snowplowable markers are nine times as expensive as RRPMs. However, if used exclusively in areas where snow is plowed, the costs for replacing the raised retroreflective markers would be much higher, because it would be necessary to replace them more often.

Cost to Obtain and Apply Word and Symbol Markings

Table 43 presents the costs to obtain and apply word and symbol markings. Twenty-two agencies reported the costs and three different units of measurement are used. Because of the smaller sample response size, and the three measurement units, data from all agencies were combined. The ratios of the relative contractor cost shows that for all three types of units, contractor-applied word and symbol markings cost more than agency-applied word and symbol markings. The data also show that those striped on-site cost less than preformed word and symbol markings.

Life-Cycle Cost

The life-cycle costs of longitudinal markings and pavement markers are discussed in this section. These costs are for state agencies only and are based on the costs to obtain, place, and repair pavement markings provided by the surveyed agencies and service lives obtained from research.

Life-Cycle Costs of Longitudinal Pavement Markings

Table 44 presents the installation cost, service life, and life-cycle costs to provide longitudinal markings of various materials by color of line for roads without RRPMs or roadway lighting. The analysis is based on the service life estimates shown previously in Table 33, and the combined cost data provided by the surveyed state agencies shown previously in Table 39.

The data for the three road types (Table 6 in chapter 3) were combined and weighted by the number of pavement-marking lines (or pairs of lines) for this table. The ranges are also presented and represent the full range of installation costs reported by state agencies. The range of pavement-marking service lives extends from one standard deviation below to one standard deviation above the mean service life. For example, the table shows that the life-cycle cost of providing a white epoxy marking is typically $0.46/m/year ($0.14/ft/year), but can range from $0.07 to $4.36/m/year ($0.02 to $1.33/ft/year). The lower end of the life-cycle cost range is based on the lowest installation cost

TABLE 42
COST OF PAVEMENT MARKERS APPLIED BY AGENCIES AND CONTRACTORS

Transportation Agency and Pavement Marker[a]	Cost of Agency-Applied Pavement Markings			Cost of Contractor-Applied Pavement Markings			Combined Cost of Pavement Markings		
	N	Typical Cost ($/each)	Range ($/each)	*N*	Typical Cost ($/each)	Range ($/each)	*N*	Typical Cost ($/each)	Range ($/each)
State									
Raised retroreflective	6	2.86	2.00–4.00	11	4.60	2.35–8.88	17	3.98	2.00–8.88
Recessed retroreflective				4	16.63	12.50–25.00	4	16.63	12.50–25.00
Snowplowable retroreflective				9	35.98	23.80–98.00	9	35.98	23.80–98.00
Nonretroreflective	3	1.79	0.90–2.78	3	1.70	1.39–1.95	6	1.75	0.90–2.78
County									
Snowplowable retroreflective				1	38.00	38.00–38.00	1	38.00	38.00–38.00
City									
Raised retroreflective	1	1.50	1.50–1.50	1	3.25	3.25–3.25	2	2.38	1.50–3.25
Nonretroreflective	1	1.25	1.25–1.25	1	2.75	2.75–2.75	2	2.00	1.25–2.75

Note: *N* = number of survey responses.
[a]Canadian agencies did not report using pavement markers.

TABLE 43
COST OF PAVEMENT MARKERS APPLIED BY AGENCIES AND CONTRACTORS

Word and Symbol Markings	Units	Cost of Agency-Applied Markings N[a]	Typical Cost ($/unit)	Range ($/unit)	Cost of Contractor-Applied Markings N[a]	Typical Cost ($/unit)	Range ($/unit)	Combined Cost of Markings[a] N[a]	Typical Cost ($/unit)	Range ($/unit)
Preformed	Linear ft	2	0.67	0.64–0.70	1	1.45	1.45–1.45	3	0.93	0.64–1.45
Preformed	Square ft	3	19.09	12.28–25.00	5	33.96	9.80–75.00	8	28.38	9.80–5.00
Preformed	Each	2	125.00	50.00–200.00	9	209.56	50.00–306.00	11	194.18	50.00–306.00
Striped on site	Linear ft	2	0.19	0.05–0.32	2	1.21	1.20–1.22	4	0.70	0.05–1.22
Striped on site	Square ft	2	8.80	2.59–15.00	8	9.47	1.00–30.00	10	9.34	1.00–30.00
Striped on site	Each	3	83.33	15.00–175.00	3	120.00	60.00–200.00	6	101.67	15.00–200.00

Notes: Costs are in $U.S. converted at the exchange rate of $1.00 U.S. = $1.5076 Canadian (March 29, 2001). 1 ft = 0.305 m.
[a]Number of survey responses by 22 agencies: 16 state, 1 Canadian, 3 county, and 2 city.

TABLE 44
LIFE-CYCLE COST TO PROVIDE PAVEMENT MARKINGS OF VARIOUS MATERIALS BY COLOR OF LINE FOR LOCATIONS WITHOUT RRPMs OR ROADWAY LIGHTING

Material	Pavement Marking Installation Cost ($/ft) Typical	Range	Pavement Marking Service Life[a] (months) Typical	Range[b]	Life-Cycle Cost to Provide Pavement Making ($/ft/year) Typical	Range[c]
White						
Waterborne paint	0.06	0.02 – 0.20	10.4	3.1 – 17.7	0.07	0.01 – 0.76
Epoxy	0.26	0.08 – 0.65	23.0	5.9 – 40.1	0.14	0.02 – 1.33
Methyl methacrylate	1.22	0.70 – 1.53	14.4	6.8 – 22.0	1.02	0.38 – 2.70
Methyl methacrylate—profiled	1.44	1.12 – 1.75	21.0	7.6 – 34.3	0.82	0.39 – 2.76
Polyester	0.13	0.05 – 0.30	24.7	16.9 – 32.6	0.06	0.02 – 0.21
Preformed tape—profiled	2.33	1.50 – 3.10	27.4	13.8 – 41.0	1.02	0.44 – 2.70
Thermoplastic	0.32	0.08 – 0.85	26.2	12.1 – 40.3	0.14	0.02 – 0.84
Thermoplastic—profiled	0.87	0.35 – 1.30	23.8	11.1 – 36.6	0.44	0.11 – 1.41
Yellow[d]						
Epoxy	0.26	0.08 – 0.65	34.3	19.8 – 48.9	0.09	0.02 – 0.39
Methyl methacrylate	1.22	0.70 – 1.53	16.8	12.6 – 21.0	0.87	0.40 – 1.46
Methyl methacrylate—profiled	1.44	1.12 – 1.75	25.0	19.1 – 31.0	0.69	0.43 – 1.10
Polyester	0.13	0.05 – 0.30	43.8	38.0 – 49.6	0.04	0.01 – 0.09
Preformed tape—profiled	2.33	1.50 – 3.10	30.6	18.7 – 42.5	0.91	0.42 – 1.99
Thermoplastic	0.32	0.08 – 0.85	27.5	15.4 – 39.5	0.14	0.02 – 0.66
Thermoplastic—profiled	0.87	0.35 – 1.30	26.7	16.4 – 37.0	0.39	0.11 – 0.95

Note: 1 ft = 0.305 m.
[a]Service life applies to locations without RRPMs or roadway lighting.
[b]Range from one standard deviation below to one standard deviation above the mean service life.
[c]Range of cost per foot per year extends from lowest installation cost and longest service life to highest installation cost and shortest service life.
[d]Insufficient data to provide results for yellow waterborne paint.
(*Source*: Migletz et al. 2000 unpublished data.)

and the longest service life, whereas the upper end of the range is based on the highest installation cost and the shortest service life.

The service lives of today's pavement-marking materials have improved over those shown in Tables 33 and 44, which were installed in the years 1994 through 1996. For example, white profiled preformed tape shows a typical service life of 27.4 months. Profiled preformed tape is now warranted to maintain a retroreflectivity level of 100 mcd/m^2/lux for 6 years in the south and 4 years in the north. Field tests showed service lives longer than those warranted (N. Hodson, personal communication, 3M Company, March 28, 2002).

When cost is kept constant, a longer service life results in a lower life-cycle cost. Using the typical installation cost of $7.64/m ($2.33/ft) for white profiled preformed tape (Table 44) results in a typical life-cycle cost of $1.28/m/year ($0.39/ft/year) under the 6-year warranty period and $1.90/m/year ($0.58/ft/year) under the 4-year warranty period. These are substantial life-cycle cost reductions from that shown in Table 44 [$3.34/m/year ($1.02/ft/year)] (Migletz et al. 2000 unpublished data). Manufacturers should be contacted to obtain the most up-to-date cost and service life information on materials the agency is considering for pavement marking applications.

Life-Cycle Cost Including Traffic Delay and Retroreflectivity Measurement

Table 45 presents two examples showing the effect of traffic delay and retroreflectivity measurement on pavement

TABLE 45
EXAMPLE LIFE-CYCLE COSTS OF PAVEMENT MARKINGS INCLUDING INSTALLATION, TRAFFIC DELAY, AND RETROREFLECTIVITY MEASUREMENT COSTS

			Pavement Marking Costs									
Scenario	Traffic Volume (veh/h)	Material	Installation ($/mi)[a]	%	Traffic Delay ($/mi)[b]	%	Retroreflectivity Measurement ($/mi)[c]	%	Total ($/mi)[d]	%	Service Life (year)[e]	Life-Cycle Cost ($/mi/yr)[f]
Four-lane freeway	2,000	White thermo-plastic	1,690	76	104	5	444	20	2,237	100	3	746
Four-lane freeway	4,000	White thermo-plastic	1,690	47	1,472	41	444	12	3,605	100	3	1,202

Notes: 1 mi = 1.61 km; 1 ft = 0.305 m.
[a]See Table 44 for the cost of white thermoplastic. Typical cost is $0.32/ft = $1,690/mi.
[b]See Table 40 for VDOT traffic delay costs. It takes four passes with the striper to stripe both sides of a four-lane freeway.
[c]See Table 41 for West Virginia DOT retroreflectivity measurement and mobilization costs. The retroreflectivity of a 1-mile section of a four-lane freeway is measured in six passes with the mobile retroreflectometer (four edge lines and two lane lines). It is assumed that the retroreflectivity is measured twice over the 3-year service life, initially and during the service life. It is assumed that retroreflectivity measurement causes little, if any, traffic delay. Retroreflectivity is measured while traveling at highway speed up to about 55 mph.
[d]The total cost is the typical pavement marking installation cost plus traffic delay cost plus the retroreflectivity measurement cost to stripe and measure both sides of a 1-mile section of four-lane freeway.
[e]See Table 35 for the VDOT 3-year service life of white thermoplastic.
[f]The life-cycle cost is the total cost divided by the 3-year service life. The life-cycle cost without the cost of traffic delay and retroreflectivity measurement is $0.11/ft/year = $563/mi/year ($1,690/mi/3years).
(*Sources*: Migletz et al. 2000 unpublished data; Cottrell and Hanson 2001; Kenney 2001.)

marking life-cycle cost. The addition of a traffic delay and retroreflectivity measurement cost provides a more realistic estimate of what it costs to stripe a highway. The examples use the typical installation cost of white thermoplastic (Table 44), the VDOT traffic delay costs for a 1-mi section of a four-lane freeway with traffic volumes of 2,000 and 4,000 veh/h (Table 40), the West Virginia DOT retroreflectivity measurement costs using a mobile retroreflectometer (Table 41), and the VDOT 3-year service life (Table 35). The typical installation, traffic delay, and retroreflectivity measurement costs are added to obtain the total cost to stripe both sides of the highway. Dividing by the service life produces the life-cycle cost.

Traffic delay cost can be considerable and is dependent on traffic volume. Doubling the traffic volume in these examples increases the traffic delay cost by a factor of 14.

It is assumed that retroreflectivity is measured twice; initially, after markings are installed, and usually within 60 days. Measurement is done during the life of the marking to ensure that the marking is aging as intended and has not prematurely reached the end of its service life.

For the first scenario, traffic volume is 2,000 veh/h, and the life-cycle cost, without traffic delay or retroreflectivity measurement, is $563/mi/year ($1,690/mi/3 years). It is $746/mi/year, a 33% increase, when delay and measurement costs are added. Traffic delay ($104/3 years = $35/year) is only 5% of the life-cycle cost. The retroreflectivity measurement cost is 20% ($444/3 years = $148/year).

For the second scenario, traffic volume is 4,000 veh/h, and the life-cycle cost, without traffic delay or retroreflectivity measurement, is also $563/mi/year. It is $1,202/mi/year, a 114% increase, when delay and measurement costs are added. Traffic delay is 41% of the life-cycle cost, and retroreflectivity measurement cost, a constant value, is 12%. Doubling the traffic volume, from the first to second example, increases the life-cycle cost by 61%.

Life-Cycle Costs of Pavement Markers

The Oregon DOT studied the cost-effectiveness of recessed and raised pavement markers and conventional solvent paint (Hofmann and Dunning 1995). Standing water and/or debris in the recessed grooves, wear from studded tires, and abrasion from sanding material used in snowplowing operations reduced the retroreflectivity.

The life-cycle costs were evaluated to determine the equivalent uniform annual cost (EUAC) of applying these materials (Table 46).

Table 47 presents a summary of the EUAC for the three types of markings. The study was based on year 1994 dollars. The inflated cost in year 2000 dollars is presented as a comparison.

Guidelines for the selection of RRPMs or paint based on ADT, roadway alignment, and adverse winter conditions are shown in Table 48. Because pavement markers cost much more than conventional solvent, they should only be used when it is cost-effective or when needed to improve traffic safety (Hofmann and Dunning 1995). The study recommended that recessed RPMs not be used in Oregon and that conventional solvent paint and raised RPMs are more effective.

TABLE 46
OREGON DOT ASSUMPTIONS FOR YEAR 1994 COST-EFFECTIVENESS ANALYSIS

Variable	Cost/Duration
Cost of conventional solvent paint	$0.36/linear-m ($0.11/linear-ft)
Service life of conventional solvent paint	8 months
RRPMs per mile of lane line	132
Cost of raised markers	$3.00 each
Service life of raised markers	2 years
Cost of recessed markers in groove	$8.00 each
Service life of recessed markers	3 years
Discount rate	4%

TABLE 47
OREGON DOT LIFE-CYCLE COST ANALYSIS

Marking	Service Life	Year 1994 EUAC ($/mi)	Year 2000 EUAC ($/mi)[a]
Conventional solvent paint	8 months	176	202
Raised retroreflective marker	2 years	436	501
Recessed retroreflective marker	3 years	539	620

Notes: EUAC = equivalent uniform annual cost. 1 mi = 1.61 km.
[a]Year 1994 dollars inflated to year 2000 dollars using a consumer price index of 1.15 (Friedman 2000).
(*Source*: Hofmann and Dunning 1995.)

OTHER MATERIALS

Five other types of pavement markings that have the potential to improve nighttime visibility and safety are described in this section including fluorescent pavement markings, polyurea, wet reflective durable and removable tapes, the cementitious pavement marking system, and the solar light pavement marker.

Fluorescent Pavement Markings

Ultraviolet (UV) light is not visible to the human eye. When UV light strikes certain materials the wavelengths of the light become longer, creating light that is readily visible through a phenomenon known as fluorescence. Thus, UV light makes objects more visible and offers potential for improving safety (Mahach et al. 1997). Combining UV headlights on vehicles and UV-activated fluorescent materials in pavement markings could improve drivers' nighttime vision. The enhanced visibility is provided without the glare normally associated with headlamps because the UV light has a wavelength beyond the capabilities of the human eye.

Dynamic and static tests were done with 41 subjects in two groups of drivers of ages 25 to 45 and 65 and older (Mahach et al. 1997*)*. Three marking materials were used, worn and faded traffic paint, new thermoplastic, and fairly new thermoplastic with fluorescent material. The UV headlights provided a very noticeable increase in delineation visibility. The mean subjective rating of roadway delineation with UV headlights was 19% higher than with regular low beams. In the static tests, drivers were able to see an average of 25% farther along the edge line and 29% more of the center skip lines. The subjective rating of visibility increased 47% with the UV headlights.

Another phase of the research evaluated UV headlights relative to halogen, high-intensity discharge, high-output halogen, and thermal infrared imaging system headlights ("FHWA Studies of Fluorescent . . ." 1998). Marking materials included traffic paint, fluorescent thermoplastic, and polyurea. There were differences between the detection and recognition distances for the headlight systems, but no clear advantage for the UV system. In addition, there is concern that fluorescent markings deteriorate rapidly because markings absorb large amounts of UV rays from the sun causing rapid depletion of the fluorescing agents. Additional testing needs to be done to understand the factors involved.

Polyurea

Polyurea is a two-component, 100% solids, liquid pavement marking. It is designed for use on AC and PCC pavements where traffic is generally free rolling and which have multiple years service life remaining ("Stamark Liquid

TABLE 48
OREGON DOT GUIDELINES FOR RAISED RETROREFLECTIVE PAVEMENT MARKERS AND PAINT

Alignment	Snow Zone (elevation > 2,500 ft)	Non-Snow Zone <10,000 ADT[a]	Non-Snow Zone 10,000–30,000 ADT	Non-Snow Zone >30,000 ADT
Good	Paint	Paint	Raised paint	Raised
Poor[b]	Paint	Raised paint	Raised paint	Raised

Note: ADT = average daily traffic.
[a]Raised markers should be considered for high seasonal traffic volumes and for heavy rain and fog zones.
[b]Consider durable markings for special applications.
(*Source*: Hofmann and Dunning 1995.)

. . ." 1999). The material has a track-free drying time of 3 min or less. Retroreflectivity is provided by a combination of drop-on microcrystalline ceramic elements (index of refraction 1.9) and glass beads. Yellow beads improve nighttime yellow color. The minimum initial R_L is 1,000 mcd/m^2/lux for white and 600 mcd/m^2/lux for yellow, although it can be as high as 1,400 and 850 mcd/m^2/lux, respectively. Polyurea does not contain heavy metals or chemicals containing lead. The installation cost was reported to be between $2.30 (Cottrell and Hanson 2001) and $2.95 (Iowa DOT survey response) per linear-m ($0.70 and $0.90 per linear-ft).

Wet Reflective Durable and Removable Tapes

Wet reflective durable tape is intended for use as long-term longitudinal markings ("Scotch-Lane . . ." 2000). Wet reflective removal tape is designed for work zone applications ("Scotch Lane . . ." 1999). The tapes are designed to be retroreflective under wet and dry conditions on both AC and PCC pavements. The material uses wet reflective "enclosed lens optics" supported by a thin, flexible, conformable backing. It is reinforced by a structured medium and precoated with a pressure-sensitive adhesive for application in temperatures above 10ºC (50ºF). The initial retroreflectivity is 750 mcd/m^2/lux and 450 mcd/m^2/lux for white and yellow markings, respectively, for both dry and wet/rainy conditions.

Cementitious Pavement Marking System

The cementitous pavement marking system is a polymer-modified cementitous material with integral glass beads and pigment that is reported to be very durable ("Lumimark" 2000). It is designed for new or existing PCC highways, bridges, airports, barrier walls, and curbs. It is integrated into the pavement rather than applied to the surface, with glass beads and pigment incorporated into the cement mixture that is applied into a groove cut into the pavement. The rectangular groove is 4.76 to 6.35 mm (three-sixteenths to one-quarter inch) deep. It can be installed in temperatures ranging from 4.4 to 43.3ºC (40 to 110ºF).

Solar Light Pavement Marker

The solar light pavement marker has an embedded light-emitting diode, which comes on at dusk to provide nighttime delineation of curves, medians, crosswalks, and other potentially hazardous locations. It attaches to the pavement like a conventional pavement marker, is snowplowable, and is recharged by solar power during daylight. During daylight it functions like a standard RRPM, but at night it extends the viewing distance up to 610 m (2,000 ft). There are variations on the system for fog, standing water, ice, work zones, and portable applications such as police work. One model has a trail function that emits a flashing orange display for 4 s after a vehicle passes so that following vehicles can follow the trail through, for example, fog and road spray. When the following vehicle is too close, a red light is emitted. One model can be postmounted for applications in heavy snow.

SUMMARY

Transportation agencies use longitudinal pavement markings, raised pavement markers, and word and symbol markings to provide long-term markings for their highway systems. There has been a shift away from using conventional solvent paint with a high VOC content toward waterborne paint and durable materials that provide a cleaner environment. A decision-making software program is available to help agencies select materials based on engineering and environmental performance.

Sixteen types of materials are being used for longitudinal markings, with state agencies using the largest variety. Waterborne paint is the most commonly used material (78% of the agencies), followed by thermoplastic at 69%. Waterborne paint is striped on almost 60% of the total mileage at a cost of 17% of the money spent on pavement markings. Thermoplastic is striped on almost 23% of the total mileage at a cost of 35% of the money spent on pavement markings. Agencies are using more durable pavement markings to increase the service life of pavement marking systems. Contractors apply more durable markings than agencies, many of which require specialized equipment and highly trained workers.

The service life of longitudinal pavement markings varies by color of line and type of pavement surface. At a threshold value of 100 mcd/m^2/lux, white lines have a service life of 34 months that is 42% greater than the 24-month service life of yellow lines. The longer service life of white materials shows a benefit of an all-white system of pavement markings. Lines on AC pavement have a service life of 33 months, which is 27% greater than the 26-month service life of lines on PCC pavement.

Agencies provided the unit cost for obtaining and placing each of the materials used on the agency system of highways for markings applied by agency personnel and contractors. The costs were provided for longitudinal markings, pavement markers, and word and symbol markings. The service lives, costs, and life-cycle costs of longitudinal pavement markings vary considerably by the type of marking material. The cost of traffic delay due to striping operations and retroreflectivity measurement can add significantly to the life-cycle cost of longitudinal markings.

Acceptable retroreflectivity in an RRPM is dependant on cumulative traffic volume. Retroreflectivity may last as little as 6 months on a high-volume freeway with truck traffic. The more durable and expensive RRPMs become cost-effective when the AADT reaches 10,000 veh/day/lane. Texas DOT guidelines for spot maintenance and system replacement of RRPMs have been presented. Replacement schedules of 1 year, 2 to 3 years, and 3 to 4 years are based on the level of ADT. A system of RRPMs may require annual replacement on roads with an ADT greater than 50,000 veh/day. The Georgia DOT has a 2-year replacement program. There is no clear consensus of practice with regard to the type of adhesive used with RRPMs. The Texas DOT found bituminous adhesive to be superior to epoxy adhesive in keeping the RRPM attached to the pavement on a new AC surface. The advantage that bituminous adhesive exhibits over epoxy is largely lost for older AC pavement surfaces and for pavements with truck traffic.

New products are coming on the market that can improve nighttime visibility in adverse weather and have the potential to improve traffic safety.

CHAPTER EIGHT

INVENTORY MANAGEMENT SYSTEM FOR PAVEMENT MARKINGS

Transportation agency experience with inventory management systems is described in this chapter. An inventory management system tracks the service life of pavement markings and will reduce the cost of marking a highway system by enabling transportation agencies to select cost-effective markings with increased service lives. Longer-lasting retroreflective markings that reduce traffic crashes will be the benefit of such a system.

AGENCY EXPERIENCE WITH AN INVENTORY MANAGEMENT SYSTEM

Eight agencies reported having an inventory management system. Another is implementing a system based on the MnDOT model discussed in this section. The types of systems most often used were spreadsheets and database programs, which are used for inventory and scheduling tasks. Most agencies had not used their systems long enough to know the benefits being realized, but three believed that their system was useful for inventorying the age of markings and budgeting marking replacement. Improvements needed to the inventory management systems included better input from the field, more staff, uniformity across the agency, and addition of a geographical information system (GIS) to locate markings.

One-third (17) of the responding agencies were planning to develop a computerized inventory management system. Most respondents were just starting to develop a system or stated that development was 2 to 3 years away. Some agencies are reviewing commercial systems or examining what other agencies are doing to decide how to configure their system. A few state agencies mentioned that their marking program would be included into an Integrated Maintenance Management System. Many of these systems begin with a sign inventory and then expand to include other traffic control devices. One city will not develop a system until minimum retroreflectivity requirements are finalized.

ELEMENTS OF AN INVENTORY MANAGEMENT SYSTEM

Transportation agencies are looking for ways to improve pavement-marking retroreflectivity and increase service life while minimizing the escalating costs of managing a system of pavement markings. The questions of when and where to restripe requires quantitative data, which up to now was not available. Large quantities of data are needed for establishing minimum performance standards.

The MnDOT, in a joint effort with the FHWA, has developed an inventory management system to track the useful life of pavement markings ("Pavement Marking Management System" 1998). The system uses technology to manage information and allow intelligent decisions to be made concerning pavement marking programs.

The MnDOT system starts with the Laserlux mobile pavement-marking retroreflectometer that uses 30-m (98.4-ft) geometry ("Laserlux User's Guide" 1997; Texas Transportation Institute 2000C, 2001). The pavement marking is sampled at one-third scale geometry with the Laserlux reading the marking at a point approximately 10 m (30 ft) in front of the retroreflectometer while it is driven at highway speeds, which is equivalent to a passenger car driver looking 30 m (98.4 ft) ahead of the vehicle. The data are stored along with the measurement distance, set in either metric or standard units.

The MnDOT inventory management system tracks the following:

- Installations—location, date, line, type, and quantity of material;
- Inventory;
- Retroreflectivity;
- Specific action steps;
- Costs—employee, equipment, material; and
- Suppliers.

Installations

Complete information about pavement marking installations is essential to effectively manage the system and is considered the heart of the system. To make intelligent decisions, managers need complete installation information to identify problem areas, determine maintenance schedules, and effectively plan budgets.

Decision making requires complete and accurate tracking of installations. Critical components are the location, date, type of line, material type, and quantity of material used at the time of installation. The location portion of the system should track where, or from reference point to reference point, the markings were installed. Each centerline, edge line, lane line, etc., should be tracked by the date that it was installed. The type of material that was installed, for example, waterborne paint, tape, thermoplastic, or epoxy, is recorded. Agencies may use different material types within the same locations, which is not a problem for the system. For example, tape may be specified for the lane lines and epoxy for the edge lines. The system is capable of tracking multiple material installations. Tracking material quantity is one of the primary considerations of the system.

Inventory

Many of the decision options that systems can provide depend on accurately tracking each and every pavement marking installation on a daily basis. Without the tracking process, developing an inventory could be very expensive. This is one of the principle reasons that both the department maintenance and contracted input screens were developed. One major problem with tracking any inventory is that the database (i.e., the inventory) is usually out of date by the time it is entered into a system. This inventory will never be out of date if markings are being tracked as they are installed.

Retroreflectivity

Both hand-held or mobile 30-m (98.4-ft) instruments can be used to measure marking retroreflectivity. Collecting retroreflectivity with either type of instrument, however, is expensive. Before determining the type of system to use, either hand-held or mobile, agencies should consider one or more of the following:

- ADT count for the area to be measured,
- Length of segment,
- Location of line to be measured (i.e., centerline versus edge line),
- Number of readings per segment required, and
- Traffic control requirements.

Collection of retroreflectivity measurements is done so that the system can track the life cycles of the various materials. The MnDOT system allows inspectors to collect retroreflectivity data and store it in computerized tables for future reference. The frequency at which measurements are collected depends on the marking material and the ability to collect measurements over the agency system highways. Ideally, the retroreflectivity of every marking is measured shortly after it is installed to get the initial reading of the service life. It may not be possible for an agency to measure every marking; therefore, a sampling plan is needed to obtain a representative sample by striping contractor, material manufacturer, road type, type of line, ADT level, etc. Periodic measurements of retroreflectivity are also needed to determine the end of service life. A material such as waterborne paint with a service life of 1 year or less would require measurements at 6-month intervals. A more durable material with a service of 3 years would be measured on an annual basis.

Specific Action Steps

Once life cycles are established for each type of marking material used the agency will have many options. The ability to determine when or how often markings are in need of maintenance is of primary concern. The system gives the agency the ability to record specific action steps. In addition to enabling effective maintenance, the system can provide an agency with priority striping routes and information for analysis of persistent problems. The system records steps taken, or not taken, for defense against tort liability claims.

These benefits cannot be gained without timely, efficient, and comprehensive recording practices. The memo field in either the maintenance or construction daily log offers agencies the opportunity to record and store this information. The MnDOT includes some of the following in its memo field:

- If an area is reported as being deficient, record the source of the information. For example, a comment or complaint from an agency employee, private citizen, public official, contractor, or in-house inspector.
- Record specific actions taken. For example, location of re-inspected and retroreflectivity readings taken or additional traffic-control devices applied.
- Record reviewer name and date.

Costs

The MnDOT system is designed to provide the data needed to manage striping costs. It makes sense to only replace pavement markings that need replacement, and only markings that are at the end of their service life should be replaced. Pavement markings themselves are only one part of the cost equation. This system enables agencies to track employee, equipment, and material costs.

Suppliers

Tracking suppliers, and even more specifically material batch numbers, can answer many questions when problem installations are identified. It has been the MnDOT experience that failures can be tracked to different batches of material. The advantage of tracking these areas becomes clear when considering that other locations with the same material may also fail. Supplier information is exactly what managers/supervisors need, because the quality of supplier products can be compared, which will improve the quality of the pavement marking system.

System Software Structure

The system uses a Windows-based software program and is used with the Paradox (version 5.0 or higher) database program. Paradox is a commercially available program that can be run within and without the Windows version. The MnDOT software program assumes nothing about level of computer knowledge and is easy to use. Data can be entered into the program directly into tables or into a scripted form.

The reference manual provides the details for conducting a field survey, including using the system software. Example pictures of screen monitors are presented and show the user what to expect and how to enter data. Copies of forms are included so that manually recorded information can later be entered into the computer system.

SUMMARY

An inventory management system tracks the service life of pavement markings. It will reduce the cost of marking a highway system by enabling transportation agencies to select cost-effective markings with increased service lives. Longer-lasting retroreflective markings that reduce traffic crashes will be the benefit of such a system. Eight agencies have implemented an inventory management system and 22 agencies are planning to implement such a system.

The MnDOT has developed an inventory management system in which retroreflectivity is sampled with a 30-m (98.4-ft) retroreflectometer, either hand-held or mobile. A database program stores the information. The system tracks installations, inventory, retroreflectivity, specific action steps, costs, and suppliers.

The following questions on inventory management systems, however, remained unanswered:

- Are pavement-marking materials improving because of the knowledge learned through the system?
- Is service life improving?
- How does an agency know that materials and service life are improving?
- What feedback does an agency get to evaluate the system of pavement markings?

CHAPTER NINE

PERFORMANCE EVALUATION

After a marking material has been approved by a transportation agency it may be used for long-term pavement marking. Pavement markings are evaluated just before, during, and after they are placed. Results of the survey of when performance and evaluation practices are used by transportation agencies are discussed. Evaluation of newly placed markings and routine in-service evaluation of existing markings are described. The use of hand-held and mobile retroreflectometers shows how states are adopting a new technology—retroreflectometers with 30-m (98.4-ft) geometry. Correlation evaluations of hand-held and mobile instruments are described. A description of how one state agency incorporated the GIS into the marking program is also presented. In addition, considerations for selecting a hand-held or mobile retroreflectometer are presented.

PERFORMANCE AND EVALUATION PRACTICES

For many years the FHWA has been promoting evaluations of pavement markings using both objective and subjective techniques (Brooks 1988). Transportation agencies address evaluation techniques in specifications and guidelines. Use of evaluation techniques is becoming more widespread because of organizations like the ATSSA that present pavement marking inspection training courses at transportation agencies and seminars (*Pavement Marking Technician's Course Notebook* 1994).

Evaluation of Newly Placed Markings

Evaluations are done before, during, and after markings are placed as part of an agency's quality-control program. (See Appendix J for examples of quality-control test methods used by VDOT.) Agencies were asked how often they evaluated the retroreflectivity and performance of long-term pavement markings. Evaluations include inspection of line quality—line thickness, bead distribution, quantity of material, etc.—or measurement of the initial retroreflectivity. Thirty-five responding agencies (69%) evaluate new markings from 3 days or less to more than 1 month after installation.

Routine In-Service Evaluation of Existing Markings

Evaluations are done during the life of the marking on a regular schedule and for performance-based and warranty provisions contracts. For example, KDOT has a 180-day acceptance period for warranty contracts (*Durable Pavement Marking* 1990). Longitudinal markings are required to meet color, durability, and retroreflectivity specifications during and at the end of the acceptance period. Evaluations are also done to determine whether the marking is approaching the end of its service life. If so, the highway section can be programmed for restriping.

Fourteen surveyed agencies (27%) inspect existing pavement markings on a regular schedule, 17 agencies (33%) occasionally inspect existing markings, and 14 agencies (27%) inspect markings on special occasions to address complaints, set up striping projects, and for warranty contracts. Two agencies inspect on a random basis and four do not conduct inspections or did not state when the inspections were made.

Objective and Subjective Evaluations

Before a marking is placed on the highway, the material has been evaluated, either through in-house or national test laboratories, and has been qualified for application. Agencies were asked about the objective and subjective evaluations that are done to substantiate the retroreflectivity and performance of a long-term pavement marking after the marking is placed.

Objective evaluations are done using an instrument such as a retroreflectometer or colorimeter. For example, the instrument records the value of the retroreflectivity, which is compared with a standard specified value to determine whether the marking is acceptable.

Subjective evaluations are the most common. They require the inspector to examine the marking and use judgment, based on established guidelines, to give it a rating. For example, nighttime retroreflectivity, using vehicle headlights to illuminate the marking, is rated on a scale from zero to 10.

Both types of evaluations are needed, although the use of retroreflectometers is increasing. Agencies reported not having enough retroreflectometers for all inspectors. Even if a retroreflectometer is available to the inspector, it is difficult to measure retroreflectivity of centerlines, yellow edge lines, or lane lines with a hand-held instrument without installing work zone traffic controls for the inspector's protection. A nighttime inspection, using vehicle headlights to illuminate the marking, gives a good indication of the marking quality.

Objective Evaluations Using a Retroreflectometer

Standards addressing minimum initial and maintained retroreflectivity levels are being implemented by state agencies. The three types of retroreflectometers used by transportation agencies are the 30-m (98.4-ft) hand-held, 30-m (98.4-ft) mobile, and 12-m (39.4-ft) hand-held instruments. Four models of 30-m (98.4-ft) hand-held retroreflectometers are used by the surveyed agencies: LTL 2000, MX30, MP-30, and Retrolux 1500. The Laserlux and Ecodyn are the 30-m (98.4-ft) mobile instruments. The Mirolux 12 is the only 12-m (39.4-ft) hand-held instrument used. The Retrolux 1500 is the only 30-m (98.4-ft) instrument not evaluated under the Highway Innovative Technology Evaluation Center (HITEC) study discussed later in this chapter, because it is no longer manufactured (Texas Transportation Institute 2001). The Mechatronic FRT01 was not used by any responding agency, but it was evaluated by HITEC.

Table 49 shows the types and numbers of instruments used. Almost all of the retroreflectometer usage is at the state level and more than 70% of all retroreflectometers used are 30-m (98.4-ft) hand-held instruments. There are actually more 30-m (98.4-ft) hand-held instruments than shown in the table. Some respondents did not know the exact numbers used by their agencies. The high cost of a mobile instrument relative to a hand-held instrument and the lack of an official standard for the minimum level of retroreflectivity has kept more agencies from purchasing mobile units. There are at least 15 additional 30-m (98.4-ft) mobile instruments in the United States that are owned or used by federal and state agencies and private companies.

There are still 12-m (39.4-ft) hand-held instruments in use. At one time, there were thought to be more than 200 of these in the United States. Some agencies have adopted the 30-m (98.4-ft) geometry and stopped using the 12-m (39.4-ft) instruments. Others use both and specify retroreflectivity levels for both geometries.

Agencies were asked which types of evaluations are used to substantiate the retroreflectivity and performance of long-term pavement markings. Table 50 presents a summary of the agencies using the three objective performance evaluations with a retroreflectometer. The evaluations are defined in the table. The most frequently used is the dry performance evaluation, followed by the luminance contrast ratio. Only a few agencies evaluate wet pavement performance. It is difficult to plan for measurements in the rain, even though some retroreflectometers can measure the retroreflectivity of wet markings. More agencies will be evaluating wet performance now that standard techniques have been developed (*Measuring the Coefficient* . . . 2001; *Test Method for Measuring* . . . 2001). One agency uses colorimic spectroscopy to obtain reflectance color coordinates (X,Y). Specifications addressing wet simulation, color, and retroreflectivity are described in chapter 6.

Subjective Evaluations

Table 51 presents a summary of agencies and their use of subjective performance evaluations. All responding agencies

TABLE 49
AGENCIES USING RETROREFLECTOMETERS

		No. of Agencies Using Retroreflectometers					
Agency	*N*	30-m Hand-held	%	30-m Mobile	%	12-m Hand-held	%
State	37	30	81	4	11	14	38
Canadian	5					1	20
County	5	1	20				
City	4						
	51	31	61	4	8	15	29

	No. of Retroreflectometers Owned or Used		
Agency	30-m Hand-held	30-m Mobile[a]	12-m Hand-held
State	>155	5	49
Canadian			1
County	1		
City			
	>156	5	50

Notes: N = agencies responding to the survey. 1 ft = 0.305 m; 30 m = 98.4 ft; 12 m = 39.4 ft.
[a]There are approximately 15 additional 30-m (98.4-ft) mobile retroreflectometers owned or used by federal and state agencies and private companies.

TABLE 50
OBJECTIVE PERFORMANCE EVALUATIONS WITH A RETROFLECTOMETER

Agency	*N*	Dry Performance[a]	%	Luminance Contrast Ratio[b]	%	Wet Performance[c]	%
State	37	25	68	4	11	2	5
Canadian	5	1	20	0	0	0	0
County	5	2	40	1	20	0	0
City	4	1	25	0	0	1	25
	51	29	57	5	10	3	6

Note: *N* = number of responding agencies.
[a]Dry performance of pavement markings—Measurement of pavement-marking retroreflectivity, day or night.
[b]Luminance contrast ratio—Relative difference in retroreflectivity between a pavement-marking and the adjacent pavement surface.
[c]Wet perfomance of pavement markings—Measurement of pavement marking retroreflectivity, day or night, during condition of rain.

TABLE 51
SUBJECTIVE PERFORMANCE EVALUATIONS

Agency	*N*	Dry Performance[a]	%	Durability[b]	%	Bead Retention[c]	%	Color Scale[d]	%	Wet Performance[e]	%	Pocket Microscope[f]	%	Color Chart[g]	%	Other	%
State	37	24	65	15	41	11	30	11	30	9	24	10	27	7	19	4	11
Canadian	5	3	60	1	20	1	20	1	20	1	20	1	20	0	0	1	20
County	5	3	60	2	40	2	40	2	40	1	20	0	0	0	0	1	20
City	4	3	75	2	50	2	50	1	25	2	50	0	0	0	0	1	25
	51	33	65	20	39	16	31	15	29	13	25	11	22	7	14	7	14

Note: *N* = number of responding agencies.
[a]Dry performance of pavement markings—Subjective evaluation made at night using vehicle headlights during dry conditions (e.g., using a scale of 0 to 10).
[b]Pavement marking durability—Subjective evaluation of the material's resistance to wear and loss of adhesion to the pavement surface over time (e.g., percentage of material remaining using a scale of 0 to 10).
[c]Bead retention—Subjective evaluation of the retroreflectivity and bead distribution during the daytime under sunny conditions (e.g., using the sunlight–shadow technique with a pass or fail rating).
[d]Pavement marking color—Subjective evaluation of the marking color (e.g., using a scale of 0 to 10).
[e]Wet performance of pavement markings—Subjective evaluation made at night using vehicle headlights during conditions of rain (e.g., using a scale of 0 to 10).
[f]Pocket microscope—A microscopic evaluation of bead distribution, embedment, and damage.
[g]Pavement marking color—Subjective evaluation of yellow color using a yellow color tolerance chart of standard colors.

have specifications and guidelines addressing performance evaluations and established procedures for conducting the evaluations. Almost two-thirds of the agencies (65%) use dry performance evaluation done at night. Durability (39%), bead retention (31%), color scale (29%), and wet performance (25%) evaluations are used by at least one-fourth of the agencies. A pocket microscope (22%) is used to understand why the quality of a marking is good or bad by examining the bead distribution. The yellow color tolerance chart (14%) is a simple way to evaluate daytime color. In addition

- One agency follows ASTM D 713 standard procedures for general performance and bead retention.
- One agency conducts random, subjective evaluations of retroreflectivity and bead retention twice a year on a statewide level.
- One agency does not use any scaled techniques, but goes by subjective appearance, which can be effective, especially if an inspector had the opportunity to compare the results with those of made with a retroreflectometer. The inspector learns to relate subjective evaluations to objective evaluations and can estimate a retroreflectivity value with what is seen at night.
- Three agencies do not use any of the techniques.
- The FHWA has been promoting techniques to evaluate pavement markings and these are being used more often.

All of the techniques are used by some agencies.

CORRELATION OF RETROREFLECTOMETERS

The increasing emphasis on measuring the retroreflectivity of pavement markings, combined with the adoption of the 30-m (98.4-ft) standard for measurement geometry, is creating an expanding market for instruments using the geometry, although nonstandard instruments are still being used. Traditional methods have used hand-held retroreflectometers, which are placed manually on the pavement marking line and remain stationary while the retroreflectivity reading is made. Mobile retroreflectometers collect measurements while driving at highway speeds. Because of the differences in measurement geometry, measurement technology, and models of instruments, studies have been done to correlate the measurements. Summaries of correlation studies are presented here.

Research with Nonstandard Instruments

Research done during the years 1977 through 1996 using nonstandard instruments is summarized in an FHWA report (Migletz et al. 2000). The Mirolux 12 12-m (39.4-ft) and Ecolux 15-m (49.2-ft) hand-held retroreflectometers, and the Gamma Scientific 2000 light meter were used in 12 studies. The minimum acceptable levels of retroreflectivity identified in 10 studies ranged from 90 to 127 mcd/m^2/lux for nighttime dry pavement conditions. A minimum value of 150 mcd/m^2/lux was recommended for highways with speeds above 80 km/h (50 mph). A minimum value of 180 mcd/m^2/lux was recommended for nighttime wet pavement conditions.

FHWA Correlation Studies

Correlations between the Mirolux 12 12-m (39.4-ft) and the Retrolux 1500 30-m (98.4-ft) hand-held retroreflectometers showed that the Mirolux 12 generally produced higher readings (Migletz et al. 2000). The regression line, which had the best fit to the paired data, while passing through the origin, had a slope of 0.667, meaning that the average Retrolux 1500 hand-held instrument reading for white lines was 66.7% of the corresponding Mirolux 12 reading. The regression line that had the best fit to the paired data for yellow lines, while passing through the origin, had a slope of 0.546, meaning that the average Retrolux 1500 reading was 54.6% of the corresponding Mirolux 12 reading.

Another FHWA study compared retroreflectivity measurements of white edge lines made with mobile and hand-held instruments (Migletz et al. 2000 unpublished data). The analysis used measurements made with the following three 30-m (98.4-ft) instruments and one nonstandard instrument:

- Laserlux mobile retroreflectometer in its normal moving mode,
- Laserlux mobile retroreflectometer in a stationary mode parked on the shoulder of the road adjacent to the edge line,
- Retrolux Model 1500 hand-held retroreflectometer, and
- Mirolux Model 12 12-m (39.4-ft) hand-held retroreflectometer.

The Laserlux and Retrolux 1500 were early 30-m (98.4-ft) instruments. The Laserlux mobile retroreflectometer was not intended for use in a stationary mode, but was used in that mode for comparative purposes.

The stationary measurements were all made at the same selected location on each white edge line evaluated. The moving Laserlux reading was made in the moving mode on the same pavement marking line at the location that was closest to the location where the stationary measurements were made. There were a total of 225 sets of comparable measurements with valid data for the four measurement methods.

Figure 26 shows correlations of retroreflectometers from the best-fit regression analysis. The relationship of the readings between 30-m (98.4-ft) instruments and the Mirolux 12 12-m (39-ft) instrument is not linear. The figure shows the readings that would be expected at four levels of retroreflectivity, 100, 200, 300, or 400 mcd/m^2/lux as measured by the mobile Laserlux retroreflectometer. Of these four values, the comparison for 100 mcd/m^2/lux may be the most important, because this represents the range within which highway agencies would typically consider replacing a pavement marking. The other values are in the typical range of retroreflectivity levels for many new and existing markings. This comparison shows that when the moving Laserlux reads 100 mcd/m^2/lux, the stationary Laserlux would read 122 mcd/m^2/lux, the Retrolux 1500 would read 142 mcd/m^2/lux, and the Mirolux 12 would read 206 mcd/m^2/lux. A key concern raised by these data is that, in this critical range of retroreflectivity values near 100 mcd/m^2/lux, the Mirolux Model 12, which is still used by highway agencies, provides retroreflectivity readings over twice those provided by the moving Laserlux. The Mirolux 12 readings were equivalent to 30-m (98.4-ft) instrument readings in the range of 300 to 400 mcd/m^2/lux (Migletz et al. 2000 unpublished data). These correlation results indicate that the 30-m (98.4-ft) and Mirolux 12 12-m (39.4-ft) instruments either measure different phenomena or measure the same phenomena on different scales, which is not surprising since the two devices use different geometries. However, because no standard or "true" values of retroreflectivity were available for the measurements, no conclusions can be drawn about the relative accuracy of the two types of instruments. The 30-m (98.4-ft) geometry has been adopted as the industry standard. Measurements collected with nonstandard instruments should be interpreted cautiously knowing that instruments of different geometry do not correlate well, especially around the retroreflectivity level of 100 mcd/m^2/lux.

3M Company Correlation Study

The 3M Company evaluated four types of hand-held retroreflectometers on a set of target panels (Hodson 1999). The retroreflectometers were selected at random from state transportation agencies, and each agency did their own measurements of the panel sets. Results showed that there was considerable measurement variability between different

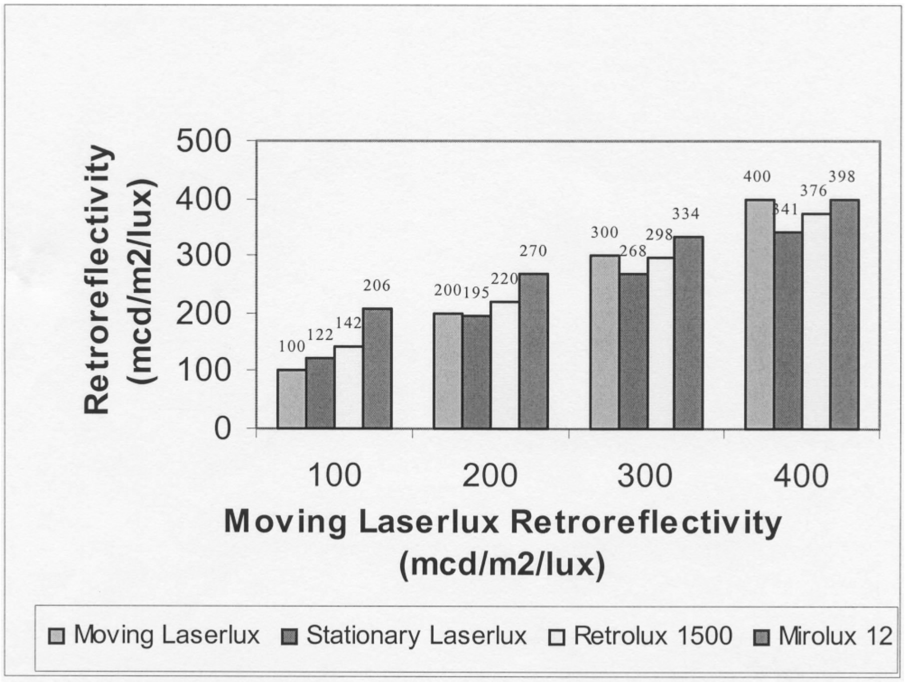


FIGURE 26 Correlation of retroreflectometers. [Notes: The Laserlux is not intended to be operated in the stationary position. Stationary Laserlux measurements were collected only for research purposes. The Laserlux and Retrolux 1500 were the early 30-m (98.4-ft) geometry (see Table 3). The Mirolux was the 12-m (39.4-ft) geometry.] (*Source*: Migletz et al. 2000 unpublished data.)

types of retroreflectometers and within each instrument type. Repeatability and reproducibility were higher at lower levels of retroreflectance. The panels were also measured in photometric laboratories. The laboratories tended to produce larger and more variable retroreflectivity values than portable retroreflectometers.

AASHTO Correlation Study

An AASHTO study compared three portable retroreflectometers, one of which used a 15-m (49-ft) geometry ("Comparison of Portable Reflectometers" 1997). These retroreflectometers were used to measure materials on the NTPEP test decks. Results showed that there were fairly good correlations for each retroreflectometer for an individual material and location, but measurements made with one type of retroreflectometer could not be accurately used to predict values using another type of retroreflectometer.

South Carolina DOT Correlation Study

The South Carolina DOT sponsored research to develop a method for evaluating pavement marking life-cycle and predictive models for different types of materials (Clarke et al. 2001 unpublished data). The following four 30-m (98.4-ft) retroreflectometers were used: Laserlux mobile, LTL 2000, MP-30, and MX30 hand-helds.

The comparison of data collected under various conditions using differing types of retroreflectometers resulted in the following conclusions:

- Daylight to nighttime data collected from a controlled test site showed that day readings were 7% greater than night readings for the MP-30 and 4% greater for the MX30.
- Equipment repeatability was the ability to get the same reading at the same exact location, generally within 1 to 2%.
- Data from a mobile unit and two hand-held units produced comparable results.

The mobile and hand-held comparison showed that areas of low readings (<80 mcd/m^2/lux), medium readings (80–200 mcd/m^2/lux), and high readings (>200 mcd/m^2/lux) would generally fall within the same ranges for hand-held and mobile unit devices. This is especially significant from a human factors standpoint because slight variations in retroreflectivity are not noticeable to the driver.

HITEC Evaluation

HITEC evaluated the 30-m (98.4-ft) retroreflectometers that were being marketed at the time of the evaluation (Texas Transportation Institute 2000A, 2000B, 2000C, 2000D, 2000E, 2000F, 2001). The evaluation had three

TABLE 52
RETROREFLECTOMETERS EVALUATED UNDER THE HITEC STUDY

Company	Model	No. Evaluated
Hand-held		
Advanced Retro Technologies	MX30	2
Flint Trading, Inc.	LTL 2000	3
Mechatronic	FRT01	2
Mirolux Products, Inc.	Mirolux Plus MP-30	3
Mobile		
Roadware, Corporation	Laserlux	1
Traffic Safety Systems	ECODYN	1

objectives, evaluate and document the performance of hand-held and mobile retroreflectometers, provide input that will aid in the development and refinement of specifications for retroreflectometers, and provide information to help users make purchasing decisions. The instruments were evaluated through laboratory and field tests.

Some materials are capable of initial levels of retroreflectivity above 1,000 mcd/m^2/lux, and transportation agencies want retroreflectometers that can substantiate the higher levels even though the human eye may not. Inspectors evaluating marking replacement needs are interested in instruments that perform well at levels of 100 mcd/m^2/lux and below. The HITEC evaluation spanned the range of retroreflectivity from less than 100 to greater than 1,000 mcd/m^2/lux.

Retroreflectometers Evaluated

The four hand-held and two mobile 30-m retroreflectometers evaluated are listed in Table 52.

Figure 27 shows pictures of the six retroreflectometers that were evaluated. A summary of general information and characteristics is presented in Table 53 for hand-held instruments and in Table 54 for mobile instruments. Detailed descriptions of the instruments are found in the summary report and the reports on the respective retroreflectometers (Texas Transportation Institute 2000A, 2000B, 2000C, 2000D, 2000E, 2000F, 2001).

Laboratory Tests

Laboratory tests were conducted at the National Institute of Standards and Technology testing facilities in Gaithersburg, Maryland, and at the FHWA Turner–Fairbank Highway Research Center in McLean, Virginia. The tests were done to determine the impact of different ambient light levels, pavement-marking retroreflectivity levels, and environmental conditions on the ability of each instrument to give consistent, precise readings. The retroreflectivity of 24 different panels consisting of three sets of eight panels each were measured. The eight panels in each set consisted of one black, five white, and two yellow panels. The black panel had an assumed value of zero mcd/m^2/lux and was used to determine the ability of an instrument to reject stray light. The impact of stray light was negligible for most instruments. The retroreflectivity levels of the white and yellow panels ranged from 61.0 to 1,133.7 mcd/m^2/lux to meet the conditions of markings found in the field, that is, from old, worn markings to new markings.

The results from the high-temperature, high-humidity; high-temperature, low-humidity; low-temperature, low-humidity; and ambient day testing were averaged together to determine the overall performance of the instrument. The measurement bias, repeatability, and reproducibility results are summarized here.

Measurement Bias

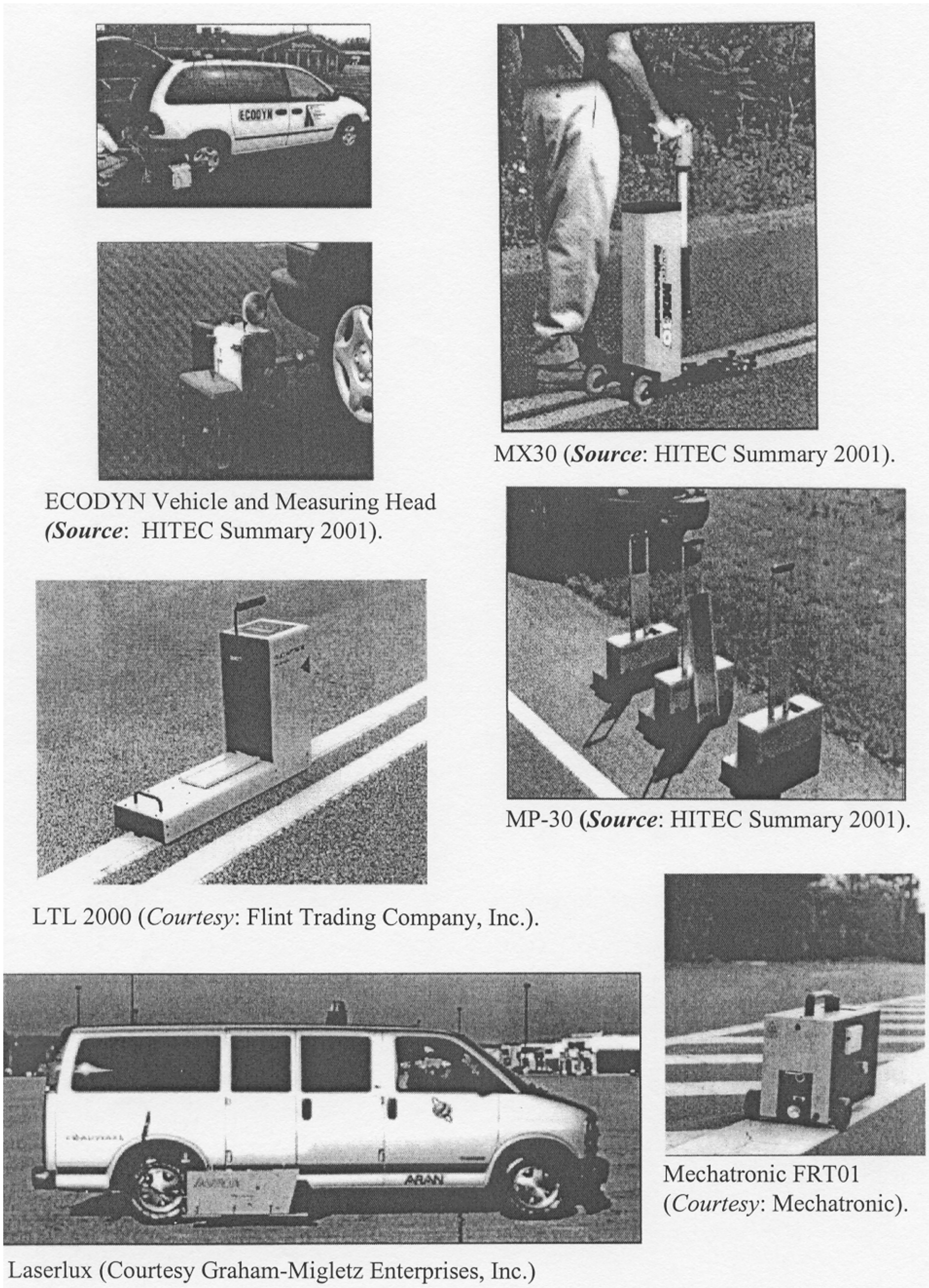
Measurement bias is the magnitude of the difference of the instrument readings and the average or "assigned" level of retroreflectivity of the test panels. In general, instruments tend to deviate more from the assigned values at lower levels of retroreflectivity.

Repeatability

Repeatability is the ability of an individual instrument to obtain identical readings at the same exact point. Repeatability for the instruments was generally very good. The ECODYN, FRT01, LTL 2000, and MX30 instruments produced average repeatabilities of fewer than ±5% for all panels. The average repeatabilities were under ±15% for the Laserlux and MP-30 and were skewed by the larger repeatabilities obtained during ambient day testing.

Reproducibility

Reproducibility is the ability of different individual instruments of the same model to produce identical readings at relatively the same point. Generally, the reproducibility of the instruments was not as good as the repeatability.



ECODYN Vehicle and Measuring Head (***Source***: HITEC Summary 2001).

MX30 (***Source***: HITEC Summary 2001).

MP-30 (***Source***: HITEC Summary 2001).

LTL 2000 (*Courtesy*: Flint Trading Company, Inc.).

Mechatronic FRT01 (*Courtesy*: Mechatronic).

Laserlux (Courtesy Graham-Migletz Enterprises, Inc.)

FIGURE 27 The 30-m retroreflectometers evaluated under the HITEC study. (*Source*: Texas Transportation Institute, HITEC Summary 2001.)

Field Tests

A series of field tests were done on two divided multilane highways in North Carolina to evaluate the performance of each instrument under real-world conditions. Each pavement marking was measured over a length of 1.6 km (1 mi). The markings at the US-1 test section (white lane/skip line, 429 mcd/m^2/lux; white edge line, 425 mcd/m^2/lux; and yellow edge line, 219 mcd/m^2/lux) were less than 1 year old and were in excellent condition. The markings on US-421 were less retroreflective (white lane/skip line, 94 mcd/m^2/lux; white right edge line, 150 mcd/m^2/lux; and yellow left edge line, 79 mcd/m^2/lux).

Each instrument produced a test site mean retroreflectivity value (e.g., ECODYN US-1 white edge line). The values for all instruments were averaged to produce a combined test site mean (e.g., US-1 white edge line). The percentage differences between the instrument and test site means are shown in Figure 28 and provide an indication of

TABLE 53
HAND-HELD RETROREFLECTOMETER CHARACTERISTICS IN 1999

	FRT01 Mechatronic	LTL 2000 Flint Trading Company, Inc.	Mirolux Plus 30 Mirolux Products, Inc.	MX30 Advanced Retro Technologies
Standards Met	EN 1436 ASTM E 1710	EN 1436 ASTM E 1710	ASTM E 1710	EN 1436 ASTM E 1710
Dimensions (L × W × H)	56 cm × 25 cm × 33 cm (22 in. × 10 in. × 13 in.)	70.5 cm × 20 cm × 47 cm (27.8 in. × 7.9 in. × 18.5 in)	56 cm × 15 cm × 19 cm (22 in. × 6 in. × 7.5 in.)	32.5 cm × 12.5 cm × 87 cm (12.8 in. × 5 in. × 34.3 in.)
Weight	12 kg (26.6 lb)	12 kg (27 lb)	7.0 kg (15.5 lb)	7.7 kg (17 lb)
Entrance Angle	88.76 deg	88.76 deg	88.76 deg	88.76 deg
Observation Angle	1.05 deg	1.05 deg	1.05 deg	1.05 deg
Measurement Range (mcd/m^2/lux)	0–2,000	0–2,000	0–2,000	0–1,999.9
Area Measured	250 mm × 50 mm (10 in. × 2 in.)	45 mm × 200 mm (1.8 in. × 7.9 in.)	90 mm × 90 mm (3.5 in. × 3.5 in.)	60 mm × 200 mm (2.4 in. × 7.9 in.)
Light Source	Gas discharge bulb	Tungsten halogen lamp	Halogen lamp	Xenon flash source
Operating Temperature	5–40°C (41–104°F)	0–45°C (32–113°F)	4–38°C (40–100°F)	0–38°C (32–100°F)
Data Storage Method	Internal memory	Internal memory	Manual data logging (optional logger available)	Internal memory
Data Storage Capacity	Up to 1,000 readings	Over 1,000 readings	N/A	Maximum of 100 files with 100 points each
Interface with PCs	Yes	Yes	No	Yes
Measure Profile Markings	Yes	Yes	Not provided	Yes
Measure Wet Markings	Yes	Yes	Not provided	Yes
Battery Life Before Recharging	At least 400 readings	About 1,000 readings	4.5 h	6,000 readings
Set-up Time	1 min	45 s	5 min	1 min
Maintenance Frequency	Yearly factory maintenance	Yearly factory maintenance	Factory maintenance only as needed	Factory service after 100,000 bulb flashes
Warranty Terms	1 yr parts	1 yr parts and labor	2 yr parts and labor	1 yr parts and labor
Service Life	At least 10 yr	10–15 yr	15–20 yr	At least 10 yr
Base Cost ($U.S.)	$14,670	$15,950	$7,500	$11,500

(*Source:* Texas Transportation Institute, HITEC Summary 2001.)

TABLE 54
MOBILE RETROREFLECTOMETER CHARACTERISTICS IN 1999

	ECODYN Traffic Safety Systems	Laserlux Roadware Corporation
Standards Met	EN 1436	EN 1436 ASTM E 1710
Vehicle Type	Minivan	454 to 680 kg (½ to ¾ ton) 9 passenger van
Maximum Speed During Data Collection	97 km/h (60 mph)	90 km/h (55 mph)
Entrance Angle	88.76 deg	88.76 deg
Observation Angle	1.05 deg	1.05 deg
Measurement Range (mcd/m^2/lux)	40–1,200	20–800 (1,500 optional maximum from factory)
Distance to Data Collection Area	6 m (19.7 ft)	10 m (32.8 ft)
Area Measured	1 m × 0.5 m (3.3 ft × 1.6 ft)	1.07 m wide (3.5 ft)
Frequency of Data Acquisition	Every 0.4 m (15.8 in.)	576 readings/min as tested (Currently offer 1,152 readings/min)
Light Source	50 W white light arc lamp measured and modulated to 865 Hz	10 mW He-Ne Laser
Operating Temperature	Not provided	0–50°C (32–120°F)
Measure Profile Markings	Yes	Yes
Measure Wet Markings	Not provided	Yes
Measure Double Lines Individually	No	Yes
Set-up Time	10 min	15 min
Maintenance Frequency	Yearly factory maintenance	Maintenance as needed
Warranty Terms	1 yr parts and labor	1 yr parts and labor
Service Life	Not provided	At least 10–15 yr
Base Cost ($U.S)	$180,000 including vehicle	$149,000 not including vehicle

(*Source:* Texas Transportation Institute, HITEC Summary 2001.)

Field Test Results

Instrument	US 1			US 421		
	White Edgeline	White Skip Line	Yellow Edgeline	White Edgeline	White Skip Line	Yellow Edgeline
ECODYN	◉	◉	⊙	⊙	●	◉
FRT01	●	●	⊙	◉	⊙	●
Laserlux	⊙	⊙	◉	◍	◉	◉
LTL 2000	●	◉	◍	●	●	◉
MP-30	⊙	●	●	●	◉	◉
MX30	●	◉	◉	⊙	◉	⊙

◉ 5% to 10% difference
⊙ 10% to 15% difference
◍ 15% to 25% difference
◎ > 25% (furthest from combined mean)

- The **ECODYN** produced an overall average that was within 10 percent of the combined average for all test sections except the US 1 yellow edgeline and the US 421 white edgeline.
- The **FRT01** produced an overall average that was within 10 percent of the combined average for all test sections except the US 1 yellow edgeline and the US 421 white skip line.
- The **Laserlux** produced an overall average that was within 10 percent of the combined average for the US 1 yellow edgeline, the US 421 white skip line, and the US 421 yellow edgeline.
- The **LTL 2000** produced an overall average that was within 10 percent of the combined average for all test sections except the US 1 yellow edgeline.
- The **MP-30** produced an overall average that was within 10 percent of the combined average for all test sections except the US 1 white edgeline.
- The **MX30** produced an overall average that was within 10 percent of the combined average for all test sections except the US 421 white edgeline and the US 421 yellow edgeline.

The field data collection with the mobile units also revealed some trends. The testing at the 3rd Street site revealed that the Laserlux usually produced lower results than the ECODYN. This may be partially caused by the ECODYN only returning the maximum value along the line. During the Colon Road testing, the Laserlux tended to produce larger values than the ECODYN.

FIGURE 28 Field data differences between the instrument test site mean retroreflectivity and the combined test site mean retroreflectivity. (*Source*: Texas Transportation Institute, HITEC Summary 2001.)

the differences between instruments. There was no way to determine which instrument was measuring the line most correctly; therefore, the combined test site mean was used as a point of comparison.

The field test retroreflectivity values, summarized in Figure 28, are presented in the HITEC summary report (Texas Transportation Institute 2001). Examination of these results showed that for the six test sites combined (three lines on US-1 and three lines on US-421), the instruments were within an 8% range (±8%) of the combined six-site mean retroreflectivity value. A 10% range is considered good. These field test results show that overall, the four hand-held and two mobile 30-m (98.4-ft) instruments are producing reliable measurements of pavement-marking retroreflectivity. In practical terms, transportation agencies can use any model of retroreflectometer to evaluate the striping done by agency forces and contractors. Striping contractors operating in different geographic areas do not need to purchase multiple models of retroreflectometers to meet local specifications.

HITEC Summary

Laboratory and field evaluations provide guidance for transportation agencies desiring to purchase or specify 30-m (98.4-ft) retroreflectometers. The laboratory tests would be difficult for a transportation agency to duplicate. Field tests, although more easily duplicated on agency highways, show the evaluation results of all instruments available at the time of the study and should be used for guiding future decisions regarding retroreflectometers. There are differences in the features and characteristics of the instruments. Readers interested in learning more about the instruments and test results should review the HITEC reports (Texas

Transportation Institute 2000A, 2000B, 2000C, 2000D, 2000E, 2000F, 2001).

There is no national calibrated standard for retroreflectivity in the United States. A national standard is critical to the success of developing minimum in-service values of pavement-marking retroreflectivity, because there is no way to calibrate instruments and evaluate the accuracy of measurements without an accepted standard.

Reference instrumentation to provide national calibration standards for retroreflectivity is being developed under NCHRP Project 5-16, National Calibration Standards for Measuring Retroreflectivity. The instrumentation will improve the accuracy of measurements collected with commercial instruments and will have the widest possible dynamic range to measure current and anticipated levels of performance of retroreflective traffic-control materials. The reference instrumentation will use modern techniques to perform calibrations in compliance with standards. It will have sufficient flexibility to measure spectral and luminous quantities of retroreflective traffic-control material over the full range of measurement angles and will have the best possible accuracy.

INCORPORATING THE GEOGRAPHICAL INFORMATION SYSTEM

Researchers for the South Carolina DOT used the GIS to develop a method for evaluating pavement marking life cycles and predictive models for materials (Clarke et al. 2001 unpublished data). Software from a GIS was used to process, manage, and display the enormous amount of data collected by mobile and hand-held instruments. Calibration was required to reconcile differences between the GIS route distances and the actual distances measured by the mobile instrument. The calibration was critical to ensure that data from hand-held and mobile instruments could be matched for comparison.

Once in the GIS, the data are plotted using the thematic mapping capabilities that show levels of retroreflectivity color-coded by direction of travel. Because of the large amount of data to be processed with the GIS, the researchers developed a multicriteria dynamic segmentation (MDS) application to more efficiently manage the retroreflectivity data. The MDS application allows on-the-fly segment-length specification, which is the length of highway over which all retroreflectivity readings are averaged and plotted on the map. Once the segment length is specified, the 30-m (98.4-ft) reference data are binned based on a user-defined set of criteria. Using binned data considerably speeds up GIS operations and makes small scale thematic maps much more readable. Maps of short sections can be plotted [e.g., 30-m (98.4-ft)] to show greater detail; for example, specific areas with low retroreflectivity. Maps of long highway sections can be plotted [e.g., 1500 m (4,921 ft)] to get an overall understanding of retroreflectivity along a route. The thematic map also includes a graph of mobile and hand-held instrument retroreflectivity versus distance. The MDS greatly aids comparison of test results.

The MDS GIS application was developed specifically for the project and proved to be a powerful tool in the analysis of the retroreflectivity data. The ability to efficiently review and query retroreflectivity data by pavement marking type, condition, location, and jurisdiction benefits both the administration and operation areas of a transportation agency.

CONSIDERATIONS FOR SELECTING A HAND-HELD OR MOBILE RETROREFLECTOMETER

Mobile and hand-held retroreflectometers each have advantages and disadvantages, and a comparison of the two types of devices is presented here (Clarke et al. 2001 unpublished data). The purchase cost of a mobile retroreflectometer instrument can exceed $180,000, including all necessary equipment, whereas the initial cost of a hand-held instrument typically ranges from $7,500 to $16,000 (year 1999 costs). The operating costs of the mobile instrument—maintenance, fuel, depreciation, technician support—are also higher, although given the ease of collecting large quantities of data unit costs may be lower.

The mobile instrument can measure retroreflectivity of all line types at highway speeds without the need for traffic controls, except for the required vehicle warning lights. Measurement of lane lines and centerlines with a hand-held instrument requires significant traffic controls to guide traffic and protect inspectors. The use of a mobile instrument may reduce the number of person-hours required to collect the data, as only one or two people are needed to drive and operate the equipment. The hand-held instrument only requires one person to take a reading, but several others may be needed for traffic control.

Another important advantage of a mobile instrument is that data are collected continuously along the roadway rather than at discrete locations as with a hand-held instrument. Data collected with a mobile instrument provides a total representation of the pavement markings along a roadway rather than a sample-based series of point locations, although a proper sampling design using the hand-held instrument produces reliable results. A hand-held instrument operates on a point of contact basis and is calibrated in a controlled environment; therefore, a hand-held instrument should provide more accurate readings.

If possible, more than one retroreflectometer should be available to the agency as a way of ensuring that any particular device is working properly. Both the hand-held and mobile instruments have unique benefits, but the final selection of the most appropriate instrument is most dependent on the type of monitoring program that the transportation agency will implement, the available work force, and resources available to conduct the work.

Selection of a retroreflectometer should consider initial capital cost, maintenance costs, manpower resources, required data accuracy, equipment reliability, and compliance with current testing standards (Clarke et al. 2001 unpublished data).

SUMMARY

Survey results showed that transportation agencies usually inspect new pavement markings within a month after they are placed, but that there is no universally accepted schedule for inspecting existing markings. The FHWA has been promoting techniques to inspect and evaluate pavement markings. Pavement marking inspection training courses are available to assist personnel in becoming more proficient with inspection procedures. Agencies have specifications and guidelines addressing performance evaluations. Objective and subjective evaluation techniques are being used by transportation agencies to evaluate pavement markings.

The use of hand-held and mobile retroreflectometers is growing, with 30-m (98.4-ft) instruments replacing 12-m (39.4-ft) instruments. Results of correlation analysis show that 30-m (98.4-ft) instruments compare more favorably among themselves than with the 12-m (39.4-ft) instrument.

Field tests of four hand-held and two mobile 30-m (98.4-ft) instruments showed that the measurements were within an 8% range (±8%) of the combined six-site mean retroreflectivity value. A 10% range is a good correlation, because it shows that these instruments are producing reliable measurements of pavement-marking retroreflectivity. A GIS using retroreflectivity data was developed to evaluate pavement marking life cycles and predictive models for materials. The ability to efficiently review and query retroreflectivity data by type of pavement marking, condition, location, and jurisdiction benefits both the administrative and operational areas of a transportation agency.

Mobile and hand-held retroreflectometers each have advantages and disadvantages. Agencies selecting a hand-held or mobile retroreflectometer should consider initial capital cost, maintenance costs, manpower resources, required data accuracy, equipment reliability, and compliance with current testing standards.

CHAPTER TEN

CONCLUSIONS

Transportation agencies use longitudinal pavement markings, pavement markers, and word and symbol markings to provide long-term markings for their highway systems. Sixty-one state, province and territory, county, and city transportation agencies and private companies in the United States and Canada were surveyed to document long-term pavement marking practices. In addition, research results were summarized. This chapter presents the conclusions of the synthesis.

- *Minimum Values of Pavement-Marking Retroreflectivity*

Drivers encounter difficulties in nighttime guidance because pavement markings often disappear, especially during rain and fog. Older drivers require more light to see delineation and are slower to react. It appears that older drivers cannot be accommodated at all speed levels with pavement markings, but that most drivers can be accommodated with properly maintained pavement markings and retroreflective raised pavement markers (RRPMs).

Section 406(a) of the 1993 Appropriations Act requires the Secretary of Transportation to revise the *Manual on Uniform Traffic Control Devices* (MUTCD) to include a standard for a minimum level of retroreflectivity that must be maintained for pavement markings and signs. The FHWA has developed MUTCD criteria for retroreflectivity of pavement markings, but no such criteria have yet been approved and implemented as a policy. The criteria are based on speed and road class, color of line, and presence or absence of roadway lighting or RRPMs. The minimum values of retroreflectivity are reduced when roadway lighting and/or RRPMs are present. In some classifications, the minimum values concur with research recommendations; however, in others they are less. To meet the FHWA minimum values, transportation agencies may have to stripe more often and increase the money spent on pavement markings.

Finding the funding for pavement markings is a major concern for transportation agencies. There is also concern about potential liability problems and the fatalities that could not be reduced should the guidelines not be met. A typical state agency may need to increase the money spent on pavement markings by $2.4 to $3.5 million per year. The increased cost of pavement markings, however, would be offset with a reduction of fewer than two fatalities on state highways, which could result from the use of more retroreflective and durable pavement markings.

State, county, and city agencies would like retroreflectivity values to be lower than those proposed by the FHWA. They also need more information on the relationship between retroreflectivity and safety, the condition of RRPM performance on minimum values, and the effect of roadway delineation and lighting on minimum values to substantiate the minimum values.

Durable markings and RRPMs can have service lives of 3 years or more. Both can have shorter lives on high-volume freeways. Service life is reduced as truck traffic increases. If the value of pavement marking retroreflectivity is reduced when RRPMs are present, it is important that the performance of RRPMs be maintained to ensure that acceptable retroreflectivity is always provided.

The FHWA is required to develop a standard for pavement-marking retroreflectivity and believes that a standard for the minimum values of pavement-marking retroreflectivity is needed to improve traffic safety. Since the FHWA proposed the guidelines for minimum values in 1998, more information has become available that can be used to evaluate and finalize minimum values.

- *Traffic Safety and Retroreflectivity*

Pavement markings have the potential to reduce traffic crashes during daylight and darkness. Although pavement markings provide daytime longitudinal guidance to help keep drivers in the travel lanes, other aspects of the roadway environment, such as the roadside alignment, also provide guidance. Drivers rely more on retroreflective pavement markings to provide guidance information during darkness than daylight.

In 1999, 23% of all traffic crashes (1,449,000) occurred under darkness during normal weather. An FHWA study of pavement-marking retroreflectivity showed an 11% reduction in nonintersection, nighttime traffic crashes occurring on dry pavements. The study did not show a reduction in nonintersection nighttime crashes on wet pavements, where more than 4% of all traffic crashes (270,920) and more than 4% of fatal crashes (1,712) occurred under darkness during rain and/or fog conditions.

Markings that can maintain acceptable levels of retroreflectivity for longer periods will reduce traffic crashes occurring at night on dry pavements. These markings will also increase the time needed before the markings are replaced or refurbished, which will reduce the exposure of striping crews to crashes from faster moving traffic.

Pavement-marking retroreflectivity under wet pavement conditions averaged only 46% of the comparable values under dry pavement conditions. Markings that would meet minimum retroreflectivity values on dry pavements would likely be unacceptable on wet pavements.

New materials are being developed that have the potential to improve the nighttime performance of pavement markings on both dry and wet pavements. More work is needed to improve the dry and wet pavement retroreflectivity of marking materials so that nighttime delineation is improved under all conditions. Improved nighttime delineation should continue to decrease crashes on dry pavements and begin to decrease crashes in rain and fog.

- *Exposure Data for Traffic Crash Analysis*

There were 10,312 traffic crashes at 55 test sites in the FHWA before-and-after study. The sample size was not large enough to provide definitive conclusions for nighttime crashes on wet pavements and for the total number of crashes occurring at night on dry and wet pavements. The traditional before-and-after study requires substantial data to develop definitive conclusions. Other methods are needed to reach definitive conclusions on the safety benefits of pavement markings.

The National Highway Traffic Safety Administration (NHTSA) traffic crash data are useful for showing the types of crashes that can be reduced by pavement markings. Any analysis of the crash reduction potential of pavement markings requires detailed data showing vehicle-miles traveled (VMT) so that accident rates can be calculated to perform a reliable analysis. For example, to determine whether a type of pavement-marking material reduces crashes occurring under darkness, VMT during daylight and darkness are required. State transportation agencies are collecting VMT data that can be summarized and presented as a nationwide statistic. To satisfy traffic crash analysis needs, VMT data would have to be classified in the same manner that much of the NHTSA fatal crash data are classified; that is, by light condition, roadway surface condition, relation to junction, speed limit, etc.

Agencies will produce more pavement-marking retroreflectivity and service life data as inventory management systems are implemented. These data, along with improved VMT and traffic crash data, will allow for more definitive analysis of the safety benefits of pavement markings.

- *European Pavement Marking Practices*

A scanning tour of European pavement marking practices recommended that all-white pavement markings and tiger tail ramp markings both be studied for U.S. implementation. Chevron markings spaced at 40 m (131 ft) to indicate the proper vehicle spacing reduce tailgating and accidents and have an 80:1 benefit-cost ratio.

The feasibility of a system of all-white pavement markings in the United States is currently being researched under NCHRP Project 4-28. Tiger tail ramp markings that separate two-lane entrance or exit ramp traffic may require changes in geometric design standards, but could have the potential to improve roadway capacity and reduce traffic conflicts at merging areas. The addition of chevron markings to traffic lanes along with the chevron marking sign could be a relatively low-cost improvement with a high safety benefit.

- *Specifications*

Specifications published by the FHWA, transportation agencies, the American Society for Testing and Materials (ASTM), and the European Committee for Standardization (CEN) address all aspects of pavement markings, including where to place markings, types of materials to use, surface preparation, application requirements, evaluation procedures, and procedures for marking removal. Seventy-five percent of the agencies were satisfied with their specifications. Although most agencies are confident that they are receiving good materials, they are less sure that the application of markings is adequate. Variations in specifications and quality-control procedures exist between agencies. Both transportation agencies and the pavement marking industry believe that inadequate quality-control and inspection at the time of application is a major problem. Industry also believes that inconsistent use and enforcement of specifications is a problem. Both believe that nighttime visibility can be increased through improved quality control and inspection programs. Agencies are also starting to use more performance-based and warranty provisions contracts for application of durable materials to place more responsibility for quality markings on contractors.

- *Labor Shortage and Public–Private Cooperation*

Training courses are available to enable striping personnel to become more proficient with inspecting and evaluating marking applications. There is a labor shortage for both agencies and the industry. Agencies cited problems in keeping the staff needed to maintain a marking program, including engineers, inspectors, and striping crew personnel. The industry is having trouble finding qualified workers because of a tight labor market. Some agencies are alleviating the staff shortage problem by having more striping done under contract and less by agency personnel. Use of more durable marking materials requires more sophisticated equipment and skilled workers. The trend of having more striping work done under contract will continue. Pavement marking companies that can develop a closer partnership with transportation agencies can help improve the performance of pavement markings while improving their business.

- *Pavement-Marking Materials*

Longitudinal pavement markings, pavement markers, and word and symbol markings are used to provide long-term pavement markings. There are 16 types of longitudinal marking materials in use. Waterborne paint is the most common and is used by 78% of transportation agencies, followed by thermoplastic at 69%. Waterborne paint is striped on almost 60% of the state highway mileage at a cost of 17% of the state agency pavement marking budget. Thermoplastic is striped on almost 23% of the state highway mileage at a cost of 35% of the budget.

Retroreflective raised, retroreflective recessed, snowplowable retroreflective, and nonretroreflective pavement markers are the four types of thermoplastic being used. Only state agencies reported using the four types of markers. Approximately one-third of the agencies reported using both raised and snowplowable retroreflective markers.

About two-thirds of the agencies reported using both preformed and striped on-site word and symbol markings, which are about equally used. Preformed word and symbol markings are made of plastic and are attached to the pavement with an adhesive or bonded to the pavement surface by heating with a torch. Thermoplastic is the primary material for word and symbol markings that are striped on site, although paint is also used.

- *Service Life of Longitudinal Pavement Markings*

Retroreflectivity measurements were made at 85 study sites in 19 states over a three-and-a-half year period. The marking material, type and color of line, and the type of roadway were the primary factors considered in determining pavement-marking service life. The severity of winter climate was assessed but was not found to have a consistent effect on service life. Service lives were determined for roads without RRPMs or roadway lighting and for roads where RRPMs or roadway lighting were present. The minimum threshold values used to determine the end of service life were those proposed by the FHWA.

Service life is longer for yellow lines, because lower threshold values were used. Service life is longer when RRPMs are present, because lower threshold values were used. Service lives are likely to be shorter on freeways, where both the threshold values and traffic volumes are higher, than on non-freeways. There are substantial variations in service life, which can be attributed to the passage of time, action of traffic, exposure to ambient weather conditions, marking material specifications, quality control at the time of installation, snowplow operations, and other factors.

At the same retroreflective threshold value, the service life of longitudinal pavement markings varies by color of line. At a threshold value of 100 mcd/m^2/lux, white lines have a service life of 34 months, which is 42% greater than the 24-month service life of yellow lines. The longer service life of white materials shows a benefit of an all-white system of pavement markings.

At the same retroreflective threshold value, the service life of longitudinal pavement markings varies by type of pavement surface. At a threshold value of 100 mcd/m^2/lux, lines on asphaltic concrete (AC) pavement have a service life of 33 months, which is 27% greater than the 26-month service life of lines on portland cement concrete (PCC) pavement. The AC pavement surface texture is rougher than PCC, which contributes to the longer service lives on AC pavement.

There have been improvements to marking materials. The average service life of a material placed today may be longer than the average service life was in the years 1994 to 1996 when the researched materials were installed**.**

- *Service Life of Retroreflective Raised Pavement Markers*

Acceptable retroreflectivity and durability in an RRPM is dependant on cumulative traffic volume, including the amount of truck traffic. Service life ranges from 1 to 4 years. Retroreflectivity may last as little as 6 months on a high-volume freeway with truck traffic. The more durable and expensive RRPMs become cost-effective when annual average daily traffic reaches 10,000 veh/day per lane. Guidelines for replacement of RRPMs are based on level of average daily traffic. There is no clear consensus of practice with regard to the type of adhesive used with RRPMs. Bituminous adhesive was found to be superior to epoxy adhesive in keeping the RRPM attached to the pavement on a new AC surface. The advantage that bituminous adhesive has over epoxy adhesive is largely lost for older AC pavement surfaces and for pavements with truck traffic.

- *Life-Cycle Cost*

Agencies provided the unit cost for obtaining and placing each of the materials used on the agency system of highways for markings applied by agency forces and contractors. The costs provided for longitudinal markings, pavement markers, and word and symbol markings vary by material.

Along with service life, which was determined from FHWA research, agency costs were used to develop life-cycle costs of white and yellow markings. The service lives, costs, and life-cycle costs of longitudinal pavement markings vary considerably by the type of marking material.

The cost of traffic delay due to striping operations and the cost for measuring retroreflectivity are added to the marking material and application costs to get a more realistic estimate of life-cycle cost. As traffic volume increases, the cost of traffic delay can add a considerable amount to life-cycle costs. The cost to measure retroreflectivity with a mobile retroreflectometer is considerable and is proportional to the number of lanes, but not traffic volume.

- *Inventory Management System*

An inventory management system tracks the service life of pavement markings. Eight surveyed agencies have implemented an inventory management system and 22 are planning to implement a system. Agencies responding to the survey have not had enough experience with an inventory management system to realize benefits. Other agencies that have experience with an inventory management system did not respond to the survey.

The following questions on inventory management systems remained unanswered:

- Are pavement-marking materials improving because of the knowledge learned through the system?
- Is service life improving?
- How does an agency know that materials and service life are improving?
- What feedback does an agency get to evaluate the system of pavement markings?

- *Performance Evaluation*

Objective and subjective evaluation techniques are being used by transportation agencies to evaluate pavement markings. The industry standard for measuring pavement-marking retroreflectivity is the 30-m (98.4-ft) geometry. Results of correlation analysis show that 30-m (98.4-ft) instruments compare more favorably among themselves than with the 12-m (39.4-ft) instrument. Field tests of four hand-held and two mobile 30-m (98.4-ft) instruments showed that the instruments are producing reliable measurements of pavement-marking retroreflectivity. A geographical information system using retroreflectivity data was developed to evaluate pavement marking life cycles and predictive models for materials. The ability to efficiently review and query retroreflectivity data by type of pavement marking, condition, location, and jurisdiction benefits both the administrative and operational areas of a transportation agency.