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research report

Synthesis of Benefits and Costs of Alternative Lane Marking Strategies

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16. Abstract:

The Virginia Department of Transportation (VDOT) currently uses snowplowable raised pavement markers (SRPMs) to supplement longitudinal pavement markings on some facilities. SRPMs are much more visible than traditional longitudinal markings under wet, nighttime conditions. SRPMs have been reported to dislodge from pavement, however, which has raised the question as to whether alternative marking materials might be able to replace SRPMs.

The purpose of this study was to investigate the visibility performance of longitudinal pavement marking materials currently on the market. The specific objectives of this study were (1) to determine whether or not new pavement marking materials could be used in place of SRPMs; (2) if SRPMs were to be used, to develop guidelines for their installation and maintenance; and (3) to determine the costs and benefits of using SRPMs to the maximum extent possible. No new data on the visibility or durability of pavement marking materials were collected for this study. The study primarily synthesized existing research on the characteristics of different marking materials and then applied information derived from the synthesis to Virginia-specific data to estimate the impacts of using different materials. National practices for installing, inspecting, and maintaining SRPMs were also reviewed.

The results of the literature review indicated that SRPMs remain the only marking system that provides sufficient nighttime preview time at high speeds, especially under wet conditions. Further, SRPMs can improve safety in certain situations, but they can also degrade safety in other situations since drivers may travel at higher speeds when the distance they can see down the road at night increases.

Proposed guidelines for the installation and maintenance of SRPMs were developed. They recommend that SRPMs be installed on all limited access freeways, on all two-lane roads with an average daily traffic volume above 15,000 vehicles per day, and on all roads with a posted speed limit of 60 mph or greater. Several other situations where SRPMs might be installed based on engineering judgment were also identified. A proposed maintenance schedule that requires inspections every 2 to 3 years was also developed.

A conservative economic analysis indicated that the benefits of installing and maintaining SRPMs using the guidelines developed in this study outweighed the costs by more than 80 to 1, based purely on potential safety improvements on road geometries where SRPMs have been shown to improve safety. Further, VDOT can realize cost savings by discontinuing SRPM usage on low-volume facilities and by revising particular SRPM standards.

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FINAL REPORT

SYNTHESIS OF BENEFITS AND COSTS OF ALTERNATIVE LANE MARKING STRATEGIES

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ABSTRACT

The Virginia Department of Transportation (VDOT) currently uses snowplowable raised pavement markers (SRPMs) to supplement longitudinal pavement markings on some facilities. SRPMs are much more visible than traditional longitudinal markings under wet, nighttime conditions. SRPMs have been reported to dislodge from pavement, however, which has raised the question as to whether alternative marking materials might be able to replace SRPMs.

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FINAL REPORT

SYNTHESIS OF BENEFITS AND COSTS OF ALTERNATIVE LANE MARKING STRATEGIES

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INTRODUCTION

Pavement markings are one of the most fundamental ways to communicate roadway information to drivers. They serve to transmit information on lane discipline and curvature, as well as reinforce the messages of other traffic control devices. To be truly effective, pavement markings must convey information in all light and weather conditions. As a result, pavement markings on public roads contain retroreflective elements, such as glass beads, so that light from vehicle headlights is returned to the eye of the driver at night.

Although many pavement markings can provide adequate retroreflectivity under dry nighttime conditions, precipitation can dramatically reduce the visibility of most markings. When rain begins to fall, the retroreflective performance of most marking materials is significantly degraded since the retroreflective elements are no longer exposed to the air. One form of marking that has proven to be effective in wet, nighttime conditions is the raised pavement marker (RPM). RPMs consist of a prismatic reflector that protrudes above the surface of the road, effectively lifting the retroreflective element above any water that falls during precipitation. RPMs come in two basic varieties: snowplowable RPMs (SRPMs) and non-snowplowable RPMs. No part of Virginia is suitable for non-snowplowable RPMs; even the Hampton Roads District, in the warmest corner of the state, is more likely than not to deploy snowplows on its roads at least once in a given winter.

SRPMs consist of a metal casting that is attached to the pavement using an epoxy. The casting is sloped so that snowplow blades will ride over the casting during plowing operations. The casting houses a reflector that is used to provide nighttime delineation. Figure 1 shows a photograph of an SRPM. The Virginia Department of Transportation (VDOT) has installed SRPMs on many of its facilities to provide delineation during wet, nighttime conditions.

Several new longitudinal marking materials have recently come on the market that may offer improved retroreflectivity during wet, nighttime conditions as compared to traditional materials. As a result, there is a need to determine whether new marking materials could replace SRPMs. If so, guidelines for their use are needed.

Figure 1. SRPM Installed in Pavement

PURPOSE AND SCOPE

The purpose of this study was to investigate the visibility performance of longitudinal pavement marking materials currently on the market. The specific objectives were as follows:

1. Determine whether or not new pavement marking materials can be used in place of SRPMs.

2. If SRPMs are to be used, develop guidelines for their installation and maintenance.

3. Determine the costs and benefits of using SRPMs to the maximum extent possible.

No new data on the visibility or durability of pavement marking materials were collected. The study primarily synthesized existing research on the characteristics of different marking materials and then applied information derived from the synthesis to Virginia-specific data to estimate the impacts of using different pavement marking materials.

METHODS

Six tasks were conducted to achieve the study objectives:

1. Review the relevant literature.
2. Assess the visibility performance of various pavement marking materials.
3. Determine the current costs for pavement marking materials.
4. Quantify the safety benefits of SRPMs.
5. Develop guidelines for the use of SRPMs.
6. Conduct an economic analysis of pavement marking systems.

Literature Review

The literature review focused on the following topics:

- guidelines for the installation and maintenance of SRPMs

- data on the visibility, cost, and durability of marking materials, including materials in common use and more experimental materials

- information on quantitative safety impacts of using different marking materials.

The VDOT Research Library, the University of Virginia library, and relevant on-line databases were consulted to identify relevant literature.

Assessment of Visibility Performance of Various Marking Materials

The literature review provided information on the nighttime visibility of different marking materials, as well as required preview times that motorists need during wet, nighttime conditions. These data were synthesized to determine which marking materials provided adequate preview time at different speeds.

The preview time is the time that would elapse between when a driver detects a pavement marking in the distance and when he or she would reach that marking at his or her current travel speed. Required preview times reflect the time and distance required for a driver to recognize and react to the messages conveyed by pavement markings.

Determination of Current Costs of Marking Materials

The literature review provided information on the costs of different marking materials. The VDOT BidTab system was used to determine average pavement marking unit costs for VDOT projects let in 2006 and 2007. Both successful and unsuccessful bids were reviewed since pavement markings are sometimes bid as one aspect of a much larger project and the pavement marking bid was not the driving factor in the selection of a contractor. The review of the BidTab data generated unit costs for several commonly used marking materials, as well as for SRPMs. A conference call was also held with representatives of several states with experience using newer wet reflective materials. Cost data on those marking systems were gathered during the conference call.

Quantification of Safety Benefits of SRPMs

Next, the safety benefits of SRPMs were quantified to the extent possible. The literature review revealed several studies that estimated the potential safety impact of SRPMs. The models from those studies were applied to portions of the road system in Virginia to estimate potential crash reduction benefits of using SRPMs.

Development of Guidelines for Use of SRPMs

The results of the previous tasks were used to develop proposed guidelines for how VDOT should use SRPMs on the primary, secondary, and interstate system. The guidelines included

- guidance on the layout and spacing of SRPMs
- guidelines for where SRPMs should be installed
- guidelines for the maintenance and inspection of SRPMs.

The guidelines were developed with a focus on locations where there was a proven need for SRPMs because of either demonstrated safety benefits or required preview time on high-speed facilities.

Economic Analysis of Pavement Marking Systems

The costs of implementing the proposed guidelines were then assessed. The alternatives selected for evaluation had to provide adequate preview time under wet, nighttime visibility conditions and be predicted to have a neutral or positive effect on safety. Once the alternatives were identified, the costs of using the SRPMs were determined. Specific costs quantified were:

- installation costs
- maintenance costs
- road user costs attributable to marking operations.

The benefits of marking systems are derived primarily through improved safety. The dollar value of crash reductions was estimated for the road types where robust models for predicting safety performance existed. The VDOT Highway Safety Improvement Program (HSIP) costs for crashes were used to estimate a monetary benefit from crash reductions.[1] Those costs were as follows:

- *Fatality:* $3,760,000
- *Injury:* $22,900 to $188,000, depending on severity of injury
- *Property Damage Only (PDO):* $6,500.

The empirical relationship between marking visibility and crash rate is not very well established. There are at least two reasons for this: (1) the crash rate at a given location depends on a great many factors and identifying statistically the influence of any one factor is difficult, and (2) in some situations, motorists appear to increase speed when visibility distance improves, choosing in effect to capture the benefits in the form of travel time savings rather than crash cost savings. The empirical literature did provide a basis for estimating crash reduction attributable to SRPMs on two types of roads: (1) two-lane, two-way roads, and (2) four-lane highways with limited access. To provide the reader a general idea of the possible cost savings, the benefits of adding SRPMs to supplement a continuous pavement marking system were computed for the roads in Virginia that have one of these two geometries. This computation yields a decidedly conservative estimate of benefits, as potential crash benefits were not explicitly estimated for many road geometries.

RESULTS

Literature Review

The identified literature was reviewed to assess a variety of issues related to RPM performance. Specifically, the following issues were examined:

- state and national practices related to installation and maintenance of RPMs
- cost and durability of RPMs and other marking materials
- visibility characteristics of RPMs relative to other marking materials
- safety impacts of RPMs.

In many cases, the available research has focused on the performance of non-snowplowable RPMs. Although it is expected that the impact of those markers would be similar to that of SRPMs in some respects (such as safety impacts), factors such as the costs and durability of the marker are likely to be significantly different. The following sections make the distinction between SRPMs and non-snowplowable RPMs where appropriate.

RPM Installation and Maintenance Practices

National RPM Installation Standards and Guidance

Several documents provide guidance on where and how RPMs should be installed. The *Manual on Uniform Traffic Control Devices* (MUTCD) provides guidance on spacing between RPMs when used to supplement longitudinal pavement markings.[2] The MUTCD guidance for basic sections is summarized in Table 1, assuming that skip lines are 10 ft long with a 30-ft gap between lines. Table 1 shows that spacing requirements vary depending on the geometry of the road and the manner in which RPMs are used to supplement continuous markings.

Table 1. MUTCD Guidance on Spacing for Raised Pavement Markers

Location	Spacing	MUTCD Section
Typical spacing, skip lines	2N (80 ft)	3B.12, Support
Solid lines, curves, transitions, or lateral shifts	N (40 ft) or less	3B.12, Option
Straight, level freeway sections skip lines	Up to 3N (120 ft)	3B.12, Option
Left edgelines	N/2 (20 ft) or less	3B.13, Guidance

MUTCD = *Manual on Uniform Traffic Control Devices* (Federal Highway Administration, *Manual on Uniform Traffic Control Devices*, Washington, D.C., 2004). The guidance assumes that skip lines are 10 ft long with a 30-ft gap between lines.

According to the MUTCD, the sections labeled "Option" are "permissive conditions that carry no requirements or recommendations." Sections labeled "Support" are "an informational statement that does not convey any degree of mandate, recommendation, authorization, prohibition, or enforceable condition." "Guidance" sections indicate "a statement of recommended, but not mandatory, practice in certain situations." The only required standards ("Shall" conditions) for RPM spacing in the MUTCD relate to situations where RPMs act as substitutes for pavement markings (rather than supplementing other markings).[2]

The MUTCD also defines the lateral positioning of RPMs relative to longitudinal markings. The *Roadway Delineation Practices Handbook* (the *Handbook*) developed by the Federal Highway Administration (FHWA) offers guidelines on how to implement the standards in the MUTCD.[3] It provides specific details on how to implement the practices in the MUTCD, showing the locations of the RPMs relative to longitudinal stripes. Figure 2 shows the lateral positioning and spacing of RPMs for two-lane, two-way roads and multilane roads indicated by the MUTCD and the *Handbook*. Details for intersection approaches, two-way left turn lanes, transition sections, turn bays, and entrance /exit ramps are also provided in the *Handbook*.

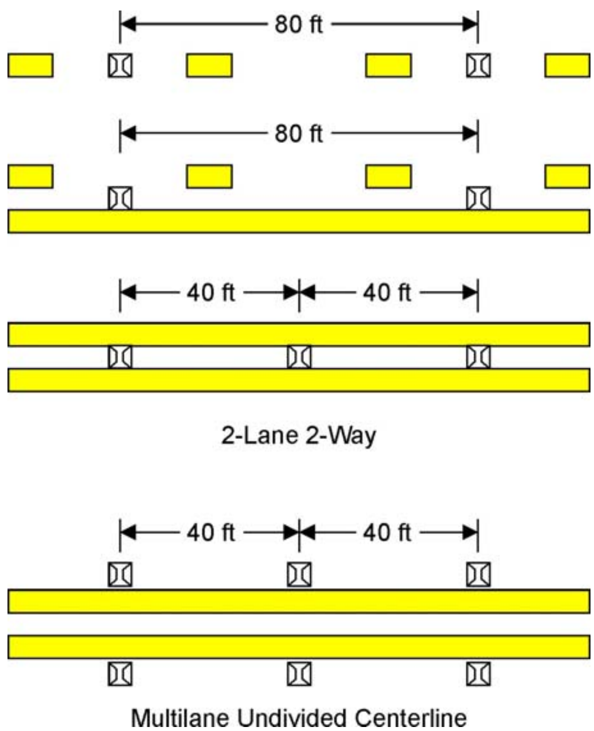

Figure 2. Recommended Layout of Raised Pavement Markers (RPM)

In addition to these detail drawings, the *Handbook* provides specific criteria for when the different RPM spacings should be used on horizontal curves on two-lane roads. Table 2 summarizes these criteria. These specific criteria are not in the MUCTD. The criteria in Table 2 imply that RPMs should be spaced more closely together as the radius of a horizontal curve become smaller.

Table 2. Recommended Spacing for Raised Pavement Markers by Degree of Curve in the *Roadway Delineation Practices Handbook*

Degree of Curve	Radius (ft)	Spacing
<3	>1,910	2N (80 ft)
3 to 15	382 through 1,910	N (40 ft)
>15	<382	N/2 (20 ft)

Source: Migletz, J., J.K. Fish, and J.L. Graham. *Roadway Delineation Practices Handbook.* FHWA-SA-93-001. Federal Highway Administration, Washington, D.C., 1994.

State Installation Practices

In some cases, states have guidelines on the usage of RPMs. A 1988 report by Arizona State University reviewed the standard spacings used by different departments of transportation (DOTs) around the nation.[4] The results of that work are shown in Table 3. The table shows that there were often considerable differences in spacing practices among states.

Further, the Arizona State University study found a number of cases where the use of RPMs was required for specific applications.[4] The results of the study are summarized in Table 4 and represent the situation at the time of the study in 1988.

Table 3. State Spacing Practices for Raised Pavement Markers According to 1988 Study by Arizona State University

Geometric Condition	Spacing
Lane lines, tangent sections	• N = 80 ft (12 states) • N = 40 ft (15 states) • N = 20 ft (1 state)
Lane lines, curved sections	• N = 80 ft (4 states). Three states noted this spacing was used when degree of curve was less than 1.15°, 3°, or 4° degrees (radii of 5,000 ft, 1,910 ft, and 1,432 ft, respectively). • N = 40 ft (15 states). Four of these states noted this spacing was used with degrees of curve (1) between 3° and 6°, (2) greater than 4°, (3) greater than 1.15°, and (4) greater than 6°. • N = 20 ft (5 states). Two states used this spacing only when degree of curve was greater than 6° (radius = 955 ft).
Centerline, passing zones	• N = 80 ft (7 states) • N = 40 ft (7 states)
Centerline, no passing zones	• N = 80 ft (4 states) • N = 40 ft (8 states) • N = 20 to 25 ft (5 states)
Intersections	• N = 80 ft (2 states) • N = 40 ft (9 states) • N = 20 ft (7 states)
Entrance/exit ramps	• N = 80 ft (2 states) • N = 40 ft (7 states) • N = 20 ft (15 states) • N = 10 ft (1 state)

Source: Matthias, J.S. *Spacing of Raised Reflective Pavement Markers*. Arizona State University, Tempe, 1988.

Table 4. State Guidelines for Installation of Raised Pavement Markers According to 1988 Study by Arizona State University

State	Guideline
Kentucky	SRPMs not used on bridge decks or local roads
Delaware	Not used on right edgeline except in special cases where additional delineation needed
South Carolina	Installed only on interstates and multilane primaries with AADT > 10,000 vpd
Mississippi	Installed on interstates and other multilane divided highways
Illinois	Installed on: • Rural 2-lane, 2-way roads with AADT > 15,000 vpd • Multilane roads with AADT > 2,500 vpd • One-way roads with AADT > 7,500 vpd • Rural horizontal curves with advisory speeds 10 mph or more below posted speed limit
Utah	Installed on all unlit exit ramps with AADT > 100 vpd
Wisconsin	Installed on: • Rural highways with AADT > 6,000 vpd • Urban streets with AADT > 15,000 vpd and no lighting • Horizontal curves where advisory speed is at least 10 mph below posted speed limit • Combinations of severe horizontal and vertical curves
West Virginia	Installed on roads with AADT > 10,000 vpd
Indiana	Installed on • 2-lane roads with AADT > 2,500 vpd • 4-lane roads with AADT > 6,000 vpd

AADT = annual average daily traffic, vpd = vehicles per day.
Source: Matthias, J.S. *Spacing of Raised Reflective Pavement Markers*. Arizona State University, Tempe, 1988.

State installation practices for RPMs were also reviewed as part of NCHRP Report 518 in 2004.[5] In this study, surveys were performed of 29 states with known RPM installations. Of these 29 states, 14 installed SRPMs and the remainder installed non-snowplowable RPMs. In some cases, this survey re-confirmed the results of the 1988 Arizona State University analysis,[4] but it also provided new information. In NCHRP Report 518, RPM usage was classified as either non-selective (RPMs installed on all facilities of a certain function classification) or selective (RPMs installed on a subset of roads based on their characteristics).[5] Ohio, Texas, and California indicated that they installed RPMs on all state-maintained roads.

Of the states that provided information on RPM usage criteria, all states installed RPMs non-selectively on the interstate system. Significant additional data obtained in this survey are shown in Table 5. Table 5 indicates that several states have specified speed or volume thresholds that must be met before RPMs could be considered for installation.

Some state DOTs list their materials or construction specifications on-line, offering a sample of differences among various state agencies. The North Carolina DOT identified several criteria for use of SRPMs in new construction and remedial treatment:[6]

- pavement surface has an estimated service life of at least 6 years

- the road carries a traffic volume of greater than 2,500 vehicles per day (vpd) (average per lane).

Table 5. Installation Guidelines for Raised Pavement Markers According to the 2004 NCHRP Report 518

State	Comments
Maryland	Installed on: • All 2-lane roads with speed limit > 45 mph • Horizontal curves where advisory speed more than 10 mph below posted speed limit • 1-lane bridges, 2-way left turn lanes (TWLTL), lane transitions
Massachusetts	Installed on all undivided highways with speed limit > 50 mph
Wisconsin	Installed on all roads with speed limit > 65 mph
Illinois	Install on: • Rural 2-lane roads with ADT > 2,500 vpd • Multilane roads with ADT > 10,000 vpd • Horizontal curves where advisory speed more than 10 mph below posted speed limit • Lane reduction transitions, rural left turn lanes, and TWLTLs
Indiana	Install on: • Rural 2-lane roads with ADT > 2,500 vpd • Multilane roads with ADT > 6,000 vpd
Kansas	Install on roads with AADT > 3,000 vpd and truck AADT > 450 vpd
Michigan	Installed on all freeways without illumination

AADT = annual average daily traffic, vpd = vehicles per day.
Source: Bahar, G., C. Mollett, B. Persuad, C. Lyon, A. Smiley, T. Smahel, and H. McGee. *Safety Evaluation of Permanent Raised Pavement Markers.* NCHRP Report 518. Transportation Research Board, Washington, D.C., 2004.

- the nighttime crash rate is higher than a critical rate (when only crash criteria are used instead of volume)

- an engineering study indicated problems because of fog-prone areas, alignment and interchange problems, narrow bridges, or locations prone to wet weather and/or wet, nighttime crash locations.

- all freeway interchanges (extending ¼ mile before and after interchange)

- complex at-grade intersections

- interstate, freeway, and high-speed multilane facilities (posted at 45 mph or greater) having three or more travel lanes in one direction.

The Alberta DOT also identified recommended guidelines for when SRPMs should be installed.[7] For two-lane roads, SRPMs were recommended for curves with a design speed of 50 mph or higher; a radius less than 11,500 ft; an AADT greater than 3,000; and demonstrated safety problems. For multilane roads, the recommended guidelines were a design speed of 50 mph or higher; a radius less than 11,500 ft; an AADT greater than 10,000; and demonstrated safety problems.

RPM Maintenance and Inspection Practices

The *Handbook* summarized some commonly used maintenance strategies that state DOTs use to examine RPMs routinely.[3] Although the authors noted that there were not much data on SRPM practices, some of the maintenance practices related to non-snowplowable RPMs may offer insight into how state DOTs maintain their markers. In some cases, states use an expected service life to schedule replacement of all RPMs on a highway.[3] The *Handbook* noted that this is often not cost-effective, as some well-functioning markers will be replaced even if they are still providing adequate visibility. Other approaches involve conducting regular inspections of RPMs and then replacing castings and lenses as needed.[3] The following criteria for replacing RPMs are used in several states that use inspection-based maintenance approaches:[3]

- *California.* RPMs are replaced when two successive retroreflective RPMs are missing.

- *Florida.* RPMs are replaced when eight or more successive RPMs are missing.

- *Massachusetts.* SRPMs are replaced if 30 percent or more are missing in an inspected section.

- *Pennsylvania.* RPMs are visually inspected when work crews are performing other work in the area. They are then replaced as needed.

Another study performed by the University of Iowa in 1998 expanded this list of maintenance practices by including several other states:[8]

- *Texas.* RPMs are replaced when 50 percent or more are missing in 1 mile of highway.

- *New Jersey.* Through a visual inspection process, lenses are replaced only if the casting is intact.

Most of the thresholds listed were generated for non-snowplowable RPMs. Since those RPMs do not have a metal casting, the potential debris impacts of RPMs becoming dislodged are not as severe as when SRPMs come loose. In most cases, nighttime inspections are conducted either annually or near the end of the expected RPM service life to determine if RPMs should be replaced. Visibility is subjectively rated, and the number of missing RPMs is noted.

NCHRP Report 518 summarized maintenance practices for RPMs most recently.[5] The researchers reported that Pennsylvania and Ohio replace RPM lenses on fixed 2- to 3-year cycles. Indiana defined SRPM lens replacement cycles as a function of the average daily traffic (ADT) on a road and the number of lanes present, as indicated in Table 6.[5] Higher volume roads required more frequent lens replacements. NCHRP Report 518 also found that Colorado and Iowa had removed all RPMs and stopped future installations because of high maintenance costs.

In 2005, an electronic survey on SRPMs was conducted by the Missouri DOT through the American Association of State Highway and Transportation Officials' Research Advisory Committee (AASHTO RAC) membership.[9] Twenty U.S. states and two Canadian provinces responded to the survey. Of these, 12 entities reported using SRPMs, with 3 of these respondents indicating that their use was experimental. When asked if there were any problems with the SRPMs coming loose from the pavement, 5 of the 9 entities whose use of SRPMs was

Table 6. SRPM Lens Replacement Cycle for Snowplowable Raised Pavement Markers in Indiana

No. of Lanes	Average Daily Traffic	Replacement Cycle (yr)
2	<5,000	4
	5,000 to 15,000	3
	>15,000	2
4 or more	<10,000	4
	10,000 to 30,000	3
	30,000 to 75,000	2
	>75,000 (inspected annually)	2

Source: Bahar, G., C. Mollett, B. Persuad, C. Lyon, A. Smiley, T. Smahel, and H. McGee. *Safety Evaluation of Permanent Raised Pavement Markers.* NCHRP Report 518. Transportation Research Board, Washington, D.C., 2004.

non-experimental responded that they were aware of a single or occasional occurrence. When asked if the cause of the failure was determined, hits from snowplow blades, pavement failures, and improper installation were the reasons cited most often. The DOTs of three northern states (Alaska, Montana, and Colorado) stated they do not use SRPMs because of heavy snowplow operations. The New York DOT stated they were using SRPMs less often, with wet-night reflective tape used as an alternative.[10]

Cost and Durability of Marking Materials

Given that the focus of the current study was to define life-cycle benefit and cost numbers for a variety of marking options, it is important to define typical costs and durability numbers that have been observed in previous studies. First, the durability of RPMs is discussed. Second, available durability data for other marking materials, including new wet weather reflective materials, are reviewed. Available cost information is also reviewed.

RPM Durability

Several studies have provided generalized estimates of the service life of SRPM casting and lenses. [11,12,13] Depending on the study, these estimates were developed based on field tests, opinions of knowledgeable practitioners, or models that predicted retroreflective performance. Table 7 summarizes the results of these studies.

Table 7. Service Life of Castings and Lenses of Snowplowable Raised Pavement Markers as Reported in Different Studies

Study	Year of Study	Casting Service Life	Lens Service Life
Bryden[a]	1979	10	3-4 yr
Cottrell[b]	1996	8	3
NCHRP Synthesis 371[c]	2007	4	

[a] *Source:* Bryden, J.E. *Long-Term Performance of Grooved Stripe-reflective Markers.* New York State Department of Transportation, Albany, 1979.
[b] *Source:* Cottrell, B.H. *Evaluation of Pavement Markings for Improved Visibility during Wet Night Conditions.* VTRC 96-R33. Virginia Transportation Research Council, Charlottesville, 1996.
[c] *Source:* Markow, M.J. *Managing Selected Transportation Assets: Signals, Lighting, Signs, Pavement Markings, Culverts, and Sidewalks.* NCHRP Synthesis 371. Transportation Research Board, Washington, D.C., 2007.

Several other studies have reviewed the durability of SRPMs on isolated test segments without determining an ultimate typical service life of SRPMs. In these cases, the researchers were often focused on determining how well the SRPMs adhered to the pavement over a relatively short period of time.

In 2005, the North Dakota DOT conducted a limited durability study of Stimsonite SRPMs at two locations.[14] The first location was on the left yellow edgeline of an interstate ramp with a 6,750 AADT, and the second was on the turn lanes of a rural highway with a two-way AADT of 1,600. A total of 12 markers were installed on the ramp, and 108 were installed in the turn lanes. The researchers noted that there were installation problems at both sites, which may have influenced the results. Table 8 summarizes the damage at the test sites over time. Given the small number of SRPMs and installation issues, it is difficult to extrapolate these results over a wider cross section of roadways. The researchers fitted a decay function of the form $P = \exp(-bt)$, where P is the proportion of castings intact and b is the decay rate, to the North Dakota DOT data using ordinary least squares. The fitted decay rate was $b = 0.12191$, implying an average life of 8.2 years, which is consistent with the results of the studies presented in Table 7.

In 2006, the Alberta DOT evaluated Stimsonite low profile SRPMs and 3M low profile SRPMs.[7] The SRPMs were placed on the centerline only at one site and on the centerline and shoulders at three other sites. The SRPMs used a 90-ft spacing on tangents and a 60-ft spacing on curves. The condition of the SRPMs was visually inspected annually over a 5-year period, although no data were collected in year 4. The researchers did not find any problems with the RPM castings over the 5-year inspection period, but they did find numerous failures of the RPM lenses, particularly on the shoulder installations. Table 9 summarizes the results of this study. The results indicate that SRPMs placed on the shoulder had significantly higher rates of lens failure than those placed on the centerline.

A 2007 study by the Vermont Agency of Transportation examined the durability of four types of SRPM over approximately 2.5 years.[15] Between 50 and 100 SRPMs from each manufacturer were installed, and they were visually inspected after 17 and 30 months. At 17 months, all castings were intact. At 30 months, three of the Avery Dennison castings were missing but all others were intact. Lens damage was much more prevalent. Between 37 and 65 percent of all SRPM lenses were missing or damaged. A summary of lens damage by number of months after installation is provided in Table 10. Definite differences in performance by manufacturer were noted.

Table 8. Summary of Damage of Stimsonite SRPMs Over Time in North Dakota DOT Study

Years Since Installation	Interstate Ramp			Rural Highway		
	Castings Damaged	Casting Missing	Lens Damaged	Castings Damaged	Casting Missing	Lens Damaged
1	2	0	0	0	1	0
2	5	0	0	18	2	4
3	9	0	2	38	2	7
4	12	0	2	38	2	7

Source: Doerr, G.L., R. Walker, and S. Henrichs. *Evaluation of Snowplowable Reflective Pavement Markers for Effective Delineation.* North Dakota Department of Transportation, Bismark, 2005.

Table 9. Lens Failures (%) in Alberta DOT Study

Site	Manufacturer	Location	No. of SRPMs	1 yr	2 yr	3 yr	5 yr
Hwy 21:24	Stimsonite	Centerline	89	0%	0%	0%	6.7%
		Shoulder	476	23.3%	45.5%	57.1%	72.1%
	3M	Centerline	165	1.2%	2.0%	3.0%	3.0%
		Shoulder	30	23%	23%	23%	23%
Hwy 28:04	Stimsonite	Centerline	124	0%	1.6%	1.6%	1.6%
		Shoulder	144	2.8%	17.1%	23.7%	27.1%
Hwy 33:04/06	Stimsonite	Centerline	217	4.6%	5.1%	6.9%	10.1%
		Shoulder	227	18.9%	27.8%	35.2%	57.3%
Hwy 37:04	Stimsonite	Centerline	304	0.7%	2.3%	5.2%	No data
Centerline average				1.6%	2.6%	4.2%	5.9%
Shoulder average				18.8%	35.4%	44.8%	59.2%

Source: Filice, J. Study *of Snowplowable Raised Pavement Markers*. Alberta Transportation, Edmonton, Alberta, Canada, 2006.

Table 10. Summary of Lens Damage by Manufacturer According to Number of Months After Installation in Study by Vermont Agency of Transportation

Manufacturer	17 mo			30 mo		
	% Damaged	% Missing	Total	% Damaged	% Missing	Total
Avery Dennison	2	0	2%	25	14	39%
Hallen	6	7	13%	21	16	37%
Ray-O-Lite	16	0	16%	38	4	42%
Ray-O-Lite	33	2	35%	63	2	65%

Source: Patterson, K., and J. Fitch. *Evaluation and Comparison of Snowplowable Raised Pavement Markings (SRPMs).* Vermont Agency of Transportation, Montpelier, 2007.

Durability of Other Marking Materials

A number of studies gathered information on average service life of marking materials, which is summarized in Table 11. The methodology used to determine service life varied, with some studies relying on surveys of transportation professionals or historic data from DOTs (NCHRP Synthesis 371,[13] Cottrell and Hanson,[16] the *Handbook*,[3] Carlson et al.[17]), and others using models that predicted the time before field retroreflectivity measurements of markings fell below certain thresholds (Migletz et al.,[18] NCHRP Report 392[19]). The Migletz et al. study examined marking durability in three environments: freeways, non-freeways with a speed limit of 45 mph or more, and non-freeways with a speed limit of 40 mph or less. The smaller number in Table 11 for the Migletz et al. study represents the service life on freeways, with the larger number representing service life on one of the other two types of facilities. NCHRP Report 392 used data from test decks in Pennsylvania and Alabama to develop service life estimates for when retroreflectivity would fall below 100 mcd/m^2/lux, which are shown separately. The 100 mcd/m^2/lux measurement was performed with a 12-m retroreflectometer in NCHRP Report 392,[19] whereas Migletz et al. used a Laserlux van with a 30-m geometry to develop service life estimates. The 30-m geometry is the standard, so some of the variation in the results may be attributable to differences in equipment. Table 11 summarizes these data. It should be noted that no durability data could be found for newer wet reflective pavement marking tapes.

Table 11. Service Life (in years) of Different Pavement Marking Materials According to Different Studies

Material	Color	*Roadway Delineation Practices Handbook* [a]	NCHRP Synthesis 371 [b]	Migletz et al. [c]	NCHRP Report 392[d]		Cottrell and Hanson[e]	Carlson et al. [f]
					PA	AL		
Waterborne paint	Unspecified	0.25-1.0	1.1				1	0.6-1.0
	White			0.87	2.31	3.17		
	Yellow				2.18	1.46		
Epoxy paint	Unspecified	1-2	3.3		1.57		3	
	White			1.07-3.28				
	Yellow			1.93-3.68				
Thermoplastic	Unspecified	3-5	4.2				3	1.9-4.5
	White			1.88-3.05	1.16	3.38		
	Yellow			2.06-2.82	0.65	1.54		
Profiled thermoplastic	Unspecified							1.5-4.0
	White			1.53-4.64				
	Yellow			1.96-4.23				
Profiled tape	Unspecified		6.3				6	1.6-6.0
	White			1.63-3.11	1.18	2.60		
	Yellow			1.63-3.24	1.03	2.53		
Polyester	White			1.73-2.28	3.31	13.83		
	Yellow			3.31-3.99	0.33	3.93		
Methyl methacrylate	Unspecified				0.90	1.53		1.2-5.0
	White			0.99-2.44				
	Yellow			1.30-1.71				
Profiled methyl methacrylate	White			1.17-3.83				
	Yellow			1.76-3.30				

PA = Pennsylvania results, AL = Alabama results. Materials that have cells with no value were not reviewed in the particular study.

[a] *Source:* Migletz, J., J.K. Fish, and J.L. Graham. *Roadway Delineation Practices Handbook*. FHWA-SA-93-001. Federal Highway Administration, Washington, D.C., 1994.

[b] *Source*: Markow, M.J. *Managing Selected Transportation Assets: Signals, Lighting, Signs, Pavement Markings, Culverts, and Sidewalks*. NCHRP Synthesis 371. Transportation Research Board, Washington, D.C., 2007.

[c] *Source*: Migletz, J., J. Graham, D. Harwood, and K. Bauer. Service Life of Durable Pavement Markings. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1749.* Transportation Research Board, Washington, D.C., 2001, pp. 13-21.

[d] *Source*: Andrady, A. Pavement *Marking Materials: Assessing Environment-Friendly Performance*. NCHRP Report 392. Transportation Research Board, Washington, D.C., 1997.

[e] *Source*: Cottrell, B., and R. Hanson. *Determining the Effectiveness of Pavement Marking Materials*. VTRC 01-R9. Virginia Transportation Research Council, Charlottesville, 2001.

[f] *Source*: Carlson, P., J. Miles, A. Pike, and E. Park. *Evaluation of Wet Weather and Contrast Pavement Marking Applications: Final Report.* Report 0-5008-2. Texas Transportation Institute, College Station, 2007.

Cost of Markings

Several studies have investigated the average cost to install markings by surveying state DOTs.[3,16,17,19,20] Average unit cost figures developed from the various studies are shown in Table 12. Units costs are in dollars per linear foot for markings and per RPM for SRPMs. The date of the study is also shown so that the value of money can be accounted for.

Table 12. Unit Costs of Markings ($/lf for longitudinal marking, each for SRPMs and SRPM lenses)

Marking Material	***Roadway Delineation Practices Handbook* (1994)[a]**	**NCHRP Report 392 (1997)[b]**	**Cottrell and Hanson (2001)[c]**	**NCHRP Synthesis 306 (2002)[d]**	**Carlson et al. (2007)[e]**
Waterborne paint	0.04-0.06	0.06	0.04 to 0.15	0.06	0.08
Thermoplastic	0.32-0.60	0.30	0.35	0.32	0.27-0.32
Preformed tape, flat	1.25			1.41	
Preformed tape, profiled		1.75	1.80	2.33	2.75-3.75
Epoxy	0.40-0.45	0.25	0.40	0.26	
Conventional solvent paint				0.07	
Methyl methacrylate		0.75		1.22	1.50-2.10
Thermoplastic, profiled				0.87	0.75
Polyester		0.10		0.13	
Polyurea			0.70	0.90	0.85
Rumble stripe with thermoplastic					0.50
SRPM (casting)	16.50-23.98			35.98	
SRPM (lens)	3.75				

[a] *Source:* Migletz, J., J.K. Fish, and J.L. Graham. *Roadway Delineation Practices Handbook*. FHWA-SA-93-001. Federal Highway Administration, Washington, D.C., 1994.
[b] *Source*: Andrady, A. Pavement *Marking Materials: Assessing Environment-Friendly Performance*. NCHRP Report 392. Transportation Research Board, Washington, D.C., 1997.
[c] *Source*: Cottrell, B., and R. Hanson. *Determining the Effectiveness of Pavement Marking Materials*. VTRC 01-R9. Virginia Transportation Research Council, Charlottesville, 2001.
[d] *Source*: Migletz, J., and J. Graham. *Long-Term Pavement Marking Practices*. NCHRP Synthesis 306. Transportation Research Board, Washington, D.C., 2002.
[e] *Source*: Carlson, P., J. Miles, A. Pike, and E. Park. *Evaluation of Wet Weather and Contrast Pavement Marking Applications: Final Report*. Report 0-5008-2. Texas Transportation Institute, College Station, 2007.

Although Table 12 shows the installation costs for the various marking materials, it does not include delays that may be incurred by drivers as a result of striping operations. Obviously, more durable markings would require less maintenance, translating into fewer potential delays to motorists because of restriping operations. Cottrell and Hanson made the only attempt in the literature to quantify the potential user delay implications of different marking materials.[16] They used a CORSIM model to evaluate 11 combinations of lane configurations and traffic volumes. In some cases where the road was near capacity, user delay costs from striping operations can be significant. In fact, Cottrell and Hanson found that user delay costs can equal installation costs for paint restriping on higher volume roads. Generalizing user delays can be difficult, however, given site-specific characteristics, especially on arterial routes.

Nighttime Visibility of SRPMs and Other Marking Materials

SRPMs are installed to provide additional visibility during nighttime conditions, especially during rain. As a result, studies that examined the visibility of SRPMs and other marking materials were assessed in order to assess the degree to which SRPMs were visible under a variety of conditions. Major studies that performed human factors evaluations of pavement marking visibility are discussed here.

Studies by the Virginia Tech Transportation Institute

VDOT, in cooperation with the FHWA, recently funded several research projects that investigated the visibility of several pavement marking materials under wet conditions at the Virginia Smart Road.[21,22] The first phase of the project evaluated the retroreflectivity of six types of markings using a passenger vehicle and a truck.[21] This was a static test, where the observers viewed white skip lines from a vehicle that was not in motion. Thirty-three drivers with an average age over 70 were used as study subjects to evaluate the maximum distance at which the markings were visible. In all cases, markings were in good condition and had not been subjected to extensive traffic loads. The markings were evaluated while dry and while being subjected to an 0.8 in/hr rain condition.

The SRPMs were generally found to perform very well during the static tests. Table 13 shows that the SRPMs were visible from a greater distance than any other type of marking under both wet and dry conditions. Under wet conditions, wet reflective tape had the next best visibility distance, but the distance was still substantially less than with the SRPMs. SRPMs were also usually subjectively ranked more highly than other materials by the study subjects.

The researchers also investigated the luminance of each marking under wet conditions.[21] The SRPMs once again had the highest luminance of the various methods evaluated. The wet reflective tape was the best option among the continuous marking systems, followed by the semi-wet reflective tape and the profiled thermoplastic. Although the SRPMs performed the best, it is difficult to make a direct comparison between a continuous marking system and SRPMs.

A second phase of this test evaluated visibility using a dynamic evaluation where drivers were in motion.[22] In this test, four marking materials were evaluated: paint and regular beads, paint and large beads, profiled thermoplastic, and wet reflective tape. SRPMs were not explicitly examined. Of these four materials, the wet reflective tape performed the best across a variety of conditions.

Table 13. Summary of Visibility Distance Results from First Phase of Virginia Tech Transportation Institute Study (ft)

Marking	Dry Condition	Rain Condition
SRPM	442	415
Paint with standard beads	291	73
Paint with large beads	284	88
Profiled thermoplastic	339	201
Wet retroreflective tape	329	280
Semi-wet retroreflective tape	322	200

Source: Gibbons, R.B., J.M. Hankey, I. Pashaj, B.H. Cottrell, and C. Anderson. *Wet Night Visibility of Pavement Markings*. VTRC 05-CR3. Virginia Transportation Research Council, Charlottesville, 2004.

Evaluations by the Texas Transportation Institute

The Texas Transportation Institute (TTI) conducted a series of evaluations of the wet night visibility of different pavement markings. In 2005, TTI reported the results of a driver study that examined the visibility of a series of different marking materials under simulated rain conditions.[23] The primary measure of effectiveness in this study was the distance at which a driver could detect a single skip line on a road with no other markings. The rain intensity was developed based on rain intensities seen in Texas. The markings evaluated included:

- *Waterborne paint*

  — smaller beads (Texas DOT [TxDOT] Type II)
  — larger beads (TxDOT Type III)

- *Thermoplastic*

  — TxDOT Type I beads
  — TxDOT Type II beads
  — TxDOT Type III beads

- *Tapes*

  — profiled tape
  — enclosed lens tape
  — flat tape
  — profiled tape with high refractive index beads

- *Exotics*

  — methyl methacrylate with splatter pattern
  — rumble stripes
  — epoxy with large beads and Visionglow beads
  — polyurea with bead clusters

- *Non-snowplowable RPMs.*

A total of 30 drivers were tested, with 10 of these drivers being older than 55 years of age. The drivers traveled through a 1,600-ft rain tunnel at 30 mph. All markings were 4 in wide. Rainfall rates of 0.28, 0.52, 0.87 in/hr were evaluated. Marking materials were placed on an aluminum panel that was 8 ft long, rather than being placed directly on the pavement. No material was placed on the leading edge of the panel. For the rumble stripes, 0.25-in depressions were cut into the panel at 24-in spacings to simulate a rumble strip configuration.

Table 14 summarizes the results of the detection distance analysis. The statistical analysis showed that both the marking material and the rain intensity played a significant role in the detection distances. As in the study by the Virginia Tech Transportation Institute,[21] RPMs

Table 14. Detection Distances for Different Materials by Rain Intensity in Texas Transportation Institute Study

Sample	Rain Intensity		
	Low	Medium	High
Waterborne paint, Type III beads	192	166	170
Waterborne paint, Type II beads	185	152	138
Thermoplastic, Type I high refractive beads mixed with Type III	215	213	228
Thermoplastic, Type III beads	228	196	191
Thermoplastic, type II beads	189	145	142
3M 380 tape	172	199	195
3M 750 tape	421	279	316
3M 380WR tape	259	227	222
ATM 400 Series tape	240	171	187
Polyurea with bead clusters	224	240	174
Epoxy with Visionglow and Type II beads	213	220	178
Yellow splattered methyl methacrylate with Type II beads	Not available	218	188
Rumble stripes (thermoplastic with Type II beads)	179	200	160
RPMs	654	586	539

Rainfall rates were 0.28 (low), 0.52 (medium), 0.87 (high) in/hr.
Source: Carlson, P., J. Miles, A. Pike, and E. Park. *Evaluation of Wet Weather Pavement Markings: First Year Report*. Report 0-5008-1. Texas Transportation Institute, College Station, 2005.

were found to have visibility distances that far exceeded all other marking materials under all rain intensities. The 3M 750 tape was found to provide the best performance of all of the continuous marking systems.

The researchers also measured the wet, dry, and recovery retroreflectivity of the different markings using the appropriate American Society of Testing and Materials (ASTM) standards. An MX30 retroreflectometer was used to perform these measurements. No RPMs were measured, but the vertical face of the rumble stripe was measured. Table 15 summarizes the results of these measurements. The 3M A750ES and 380WR tapes again had the highest retroreflectivity of the materials tested.

A subsequent study by TTI further expanded the retroreflectivity testing.[17] In these tests, the samples were evaluated at a 2 percent cross slope to simulate performance of markings on a road with a normal crown. Table 16 summarizes the results of that evaluation. Once again, the 3M 380WR and A750ES tapes performed the best under wet and recovery conditions.

Based on their analysis, the TTI researchers concluded the following:

- During wet conditions, RPMs provided the largest detection distance, followed by the 3M A760ES and 380WR tapes. Thermoplastic with large beads performed the best of the non-tape markings.

- The researchers recommended that TxDOT continue to use a thermoplastic marking with supplemental RPMs to provide wet night visibility.

Table 15. Retroreflectivity (mcd/m^2/lux) Results for Different Materials Under Different Wetting Conditions in Texas Transportation Institute Study

Material	Dry (ASTM E1710)	Recovery (ASTM E2177)	Continuous Wetting (ASTM E2176)
White waterborne paint, Type III bead	364	150	72
White waterborne paint, Type II bead	288	35	13
White LS 90 polyurea, Glomarc, Type II beads	1232	243	128
White LS50 epoxy, Type III bead	148	43	21
White LS50 epoxy, Type III bead	524	253	16
White alkyd thermoplastic, Type I, III high index beads	787	134	65
White alkyd Thermoplastic, Type I, III high index beads	646	439	56
White 3M A380I tape	746	232	75
White 3M A750ES tape	1220	1240	1250
White 3M 380WR tape	1234	975	564
White ATM 400 tape	937	509	150
Yellow 3M A380I tape	401	71	34
Yellow 3M A750ES tape	844	737	666
Yellow LS 90 polyurea, Glomarc, Type II beads	1229	150	84
Yellow ATM 400 tape	596	243	120
Yellow methyl methacrylate, Type III beads	334	113	62
White thermoplastic, Type III beads	972	282	46
White thermoplastic E16, M247 beads	510	283	25
White alkyd thermoplastic, Type II beads	524	96	22
White alkyd thermoplastic, Type II beads (Rumble Stripe)	503	185	57

Source: Carlson, P., J. Miles, A. Pike, and E. Park. *Evaluation of Wet Weather Pavement Markings: First Year Report*. Report 0-5008-1. Texas Transportation Institute, College Station, 2005.

Table 16. Retroreflectivity Results of Phase II Study by Texas Transportation Institute (mcd/m^2/lux)

Material	Bead	Color	Dry (ASTM E1710)	Recovery (ASTM E 2177)	Continuous Wetting (ASTM E2176)
380 WR tape	N/A	White	1234	975	564
Polyurea	Cluster bead	White	1232	243	128
Polyurea	Cluster bead	Yellow	1229	150	84
A750ES tape	N/A	White	1220	1240	1250
Thermoplastic	Type III	White	972	282	46
ATM 400 tape	N/A	White	937	509	150
A750ES tape	N/A	Yellow	844	737	666
Thermoplastic	Type I, III High Index	White	787	134	65
A380I tape	N/A	White	746	232	75
ATM 400 tape	N/A	Yellow	596	243	120
Thermoplastic	Type II	White	524	96	22
Epoxy	Type II	White	524	253	16
Thermoplastic	M247 and VisiBead E16	White	510	283	25
Thermoplastic rumble stripe	Type II	White	503	185	57
A380I tape	N/A	Yellow	401	71	34
Waterborne paint	Type III	White	364	150	72
Methyl methacrylate	Type III	Yellow	334	113	62
Waterborne paint	Type II	White	288	35	13

Source: Carlson, P., J. Miles, A. Pike, and E. Park. *Evaluation of Wet Weather and Contrast Pavement Marking Applications: Final Report.* Report 0-5008-2. Texas Transportation Institute, College Station, 2007.

It is worthwhile to discuss the latter recommendation in greater detail. In Texas, the RPMs are non-snowplowable and substantially less expensive than SRPMs. The TTI researchers estimated that the cost of installing and maintaining RPMs was $75 per mile at 80-ft spacings, which is substantially cheaper than the cost to install and maintain SRPMs given the data presented earlier. Given that the RPMs consistently had the largest detection distances and were substantially less expensive than the wet reflective tapes, the researchers thought that supplemental RPMs appeared to be the best marking system for TxDOT.

Studies by the University of Iowa

The University of Iowa conducted several driver studies that assessed the detection distance and retroreflectivity of several marking systems that were intended to provide high levels of wet night visibility. RPMs were not evaluated, although a variety of other newer materials were examined. These driver studies were conducted on a test track with simulated rain. In the first study, the researchers evaluated flat, patterned, and wet weather tape under dry, wet recovery (after rainfall), and raining (1 in/hr) conditions.[24] The test subjects included 18 drivers between 55 and 74 years of age, and the markings were weathered for 6 months prior to testing. The test subjects were asked to identify the earliest point where they could see the marking. The retroreflectivity of the markings was also measured.

The detection distances and retroreflectivity measurements are shown in Tables 17 and 18, respectively. The wet reflective tape had the longest detection distances and highest retroreflectivity under all conditions. The patterned tape performed better than the flat tape under wet recovery conditions, but the two materials had essentially the same level of performance during the simulated rain event.

A second study by the University of Iowa assessed paint markings with large beads, patterned tape with high index beads, and patterned tape with mixed high index beads.[25] The experimental setup was similar to that in the earlier study. Again, 18 subjects were used, and the

Table 17. Detection Distances (ft) of Marking Materials in University of Iowa Study

Material	Dry	Wet Recovery	Raining
Flat tape	267.3	80.0	80.4
Patterned tape	282.4	143.3	83.6
Wet reflective tape	381.8	249.3	185.0

Materials were evaluated under dry, wet (after rainfall), and raining (1 in/hr) conditions.
Source: Schnell, T., F. Aktan, and Y. Lee. Nighttime Visibility and Retroreflectance of Pavement Markings Under Dry, Wet, and Rainy Conditions. In *TRB 82nd Annual Meeting Compendium of Papers. CD ROM.* Transportation Research Board, Washington, D.C., 2003.

Table 18. Retroreflectivity (mcd/m^2/lux) of Marking Materials in University of Iowa Study

Material	Dry (ASTM E1710)	Wet Recovery (ASTM E2177)	Continuous Wetting (ASTM E2176)
Flat tape	321	69	30.5
Patterned tape	677.5	178.5	15
Wet reflective tape	1124.3	739	649

Source: Schnell, T., F. Aktan, and Y. Lee. Nighttime Visibility and Retroreflectance of Pavement Markings Under Dry, Wet, and Rainy Conditions. In *TRB 82nd Annual Meeting Compendium of Papers. CD ROM.* Transportation Research Board, Washington, D.C., 2003.

markings were evaluated under a combination of dry, wet recovery, and raining conditions. The materials evaluated under the dry conditions were new, unweathered material; the materials evaluated under the wet recovery and raining conditions had been weathered 1 to 2 months. Tables 19 and 20 show the detection distance and retroreflectivity results, respectively. The tape with mixed index beads had the largest detection distance and retroreflectivity across all conditions.

Table 19. Detection Distances (ft) of Marking Materials in Second University of Iowa Study

Material	Dry	Wet Recovery	Continuous Wetting
Paint with large beads	233	132	93
Tape with high index beads	299	114	79
Tape with mixed index beads	344	194	143

The materials evaluated under the dry conditions were new, unweathered material; the materials evaluated under the wet recovery and raining conditions had been weathered 1 to 2 months.
Source: Aktan, F., and T. Schnell. Performance Evaluation of Pavement Markings Under Dry, Wet, and Rainy Conditions in the Field. In *TRB 83rd Annual Meeting Compendium of Papers. CD ROM.* Transportation Research Board, Washington, D.C., 2004.

Table 20. Retroreflectivity (mcd/m^2/lux) of Marking Materials in Second University of Iowa Study

Material	Dry (ASTM E1710)	Wet Recovery (ASTM E2177)	Continuous Wetting (ASTM E2176)
Paint with large beads	319.4	126.9	49.4
Tape with high index beads	739.7	106.0	47.0
Tape with mixed index beads	881.4	200.8	156.8

The materials evaluated under the dry conditions were new, unweathered material; the materials evaluated under the wet recovery and raining conditions had been weathered 1 to 2 months.
Source: Aktan, F., and T. Schnell. Performance Evaluation of Pavement Markings Under Dry, Wet, and Rainy Conditions in the Field. In *TRB 83rd Annual Meeting Compendium of Papers. CD ROM.* Transportation Research Board, Washington, D.C., 2004.

Study by the Virginia Transportation Research Council

A study by the Virginia Transportation Research Council (VTRC) examined the performance of latex paint with large beads and waffle tape.[12] A 12-m retroreflectometer was used to collect data every 4 to 8 weeks for a 7-month period at two sites on U.S. 29 in Nelson County, Virginia. This included periods before and after snowplow operations. The largest changes in retroreflectivity were observed after a period when there were three snow events that required snowplow operations. Both the latex paint with large beads and the waffle tape lost an average of 23 percent of their initial retroreflectivity after these plowing events, although the waffle tape's initial retroreflectivity was approximately 2.6 times as large as the paint with large beads. A subjective evaluation found that the visibility of both materials was approximately the same during wet, nighttime conditions.

Safety Impacts of SRPMs and High Visibility Markings

Since SRPMs offer higher detection distances than other marking materials, they may provide safety benefits at night through better delineation. Safety improvements attributable to SRPMs were investigated since they represent the benefit that may be easiest to quantify. Studies that evaluated safety benefits of other markings were also examined, with a particular focus on the impact of retroreflectivity on safety.

Safety Impacts of SRPMs

In the 1980s, the FHWA published a report that summarized the safety effects of non-snowplowable pavement markers at sites in 12 states.[26] A variety of situations were examined, ranging from low-volume two-lane roads to multilane divided highways. Generally speaking, the research concluded that RPMs enhanced safety and improved overall delineation at hazardous locations, although safety performance was worse at some of the individual sites after the RPMs were installed. Some specific findings that directly related to safety on the interstate system included:

- RPMs significantly reduced erratic maneuvers near painted gores at interchange exits and bifurcations. This was based on a study of nine sites in New Jersey, which found statistically significant reductions in gore encroachments at six of nine sites.

- On multilane highways, the research found that RPMs improved delineation, but no statistically significant reductions in crash frequency or rate were found. A total of six multilane divided highways were assessed in New Jersey, Connecticut, Maryland, and North Dakota. No statistically significant reduction in crashes was found for any of the six sites, although in most cases only 1 year of post-installation data was available. No significant differences in 85th percentile speeds were found for the Maryland site.

NCHRP Report 518[5] sought to determine if a reduction in the crash rate occurred as a result of the use SRPMs. The focus of the research was SRPMs that had been installed since 1995. The analysis examined two-lane roads and four-lane freeways with access control. Four-lane roads with at-grade intersections were also initially selected for analysis, but there were insufficient data to generate statistically valid results. Data from Illinois, New Jersey, New York, Missouri, Pennsylvania, and Wisconsin were eventually used to assess the safety impacts. An empirical Bayes (EB) analysis was performed to create a robust safety analysis that corrected for regression-to-the-mean bias. The researchers separated the data into states that were placing the markers either non-selectively (i.e., markers placed without using crash history or other data to guide placement) or selectively based on crash history. All freeways evaluated used a non-selective application of RPMs.

On two-lane roads, the EB analysis generally showed that the safety benefits of SRPMs with regard to nighttime crashes increased as traffic volumes increased but decreased as the degree of curvature increased. This was a non-intuitive finding since it would reasonably be expected that SRPMs would create safety improvements on sharper horizontal curves, not degrade safety. The researchers hypothesized that the improved delineation was causing people to over-drive the curve. If drivers were traveling at higher speeds because of the better delineation, they may have been traveling too fast for the curve geometry. Since longer segments of road were examined, this finding applies for large stretches of road and may not be applicable to spot treatments.

The researchers used the index of effectiveness (θ) results from the EB analysis to generate a multivariate model to describe θ as a function of traffic volume and degree of curvature. The θ value estimates the proportion of crashes that would have occurred at a site if SRPMs were installed relative to a no-SRPM baseline condition, essentially representing 1 – the accident reduction factor (ARF). Other factors such as lane width and SRPM spacing were also evaluated but were not found to improve the model by a statistically significant margin. The model developed for nighttime crashes at two-lane sites is shown in Equation 1:

$$\theta_{site} = 1.1573 - 0.1700 AADT2 - 0.4004 AADT3 + 0.2736 DOC \quad \text{[Eq. 1]}$$

where

AADT2 = 1 if 5,000 < AADT ≤ 15,000, 0 otherwise
AADT3 = 1 if 15,000 < AADT ≤ 20,000, 0 otherwise
DOC = 1 if the degree of curvature is > 3.5, 0 otherwise.

A similar process was repeated for the four-lane freeways using data from Missouri, New York, and Pennsylvania. Because of the relatively homogeneous geometric design of these facilities, only AADT was found to influence the safety impact of SRPMs. The model for nighttime crashes on four-lane freeways is shown in Equation 2:

$$\theta_{site} = 1.131 - 0.193 AADT2 - 0.458 AADT3 \quad \text{[Eq. 2]}$$

where

AADT2 = 1 if 20,000 < AADT ≤ 60,000, 0 otherwise
AADT3 = 1 if AADT is > 60,000, 0 otherwise.

In both cases, the researchers found that SRPMs may not provide a safety benefit at low traffic volumes. As volumes increase, the potential safety benefit of the SRPMs increases.

Safety Impact of Other Markings

Several studies have attempted to assess the safety impacts of different marking materials or different levels of retroreflectivity. The study reported in NCHRP Web-Only Document 92 attempted to determine whether the retroreflectivity of pavement markings could be correlated with safety.[27] The researchers analyzed 118,000 crashes from California that occurred since the late 1990s. These represented 8 years of data from more than 5,000 miles of road. Multilane arterials, freeways, and two-lane roads were examined, and the road classification and local climate were considered. Data from the National Transportation Product Evaluation Program (NTPEP) were used to try to quantify how the retroreflectivity of markings declined over time since there were no direct retroreflectivity measurements of the roads being studied. A time series approach was then used to assess how the estimated marking retroreflectivity correlated with safety. The researchers found that there was no relationship between the predicted marking retroreflectivity and safety when night, non-intersection crashes were examined. This analysis was obviously limited by the fact that retroreflectivity values were not directly measured in the field. The NTPEP data may or may not be a good measure of how retroreflectivity declines over time at real field sites.

NCHRP Synthesis 306 reported unpublished data from another study that evaluated safety at 55 sites.[20] These 55 sites included 36 freeways, 8 arterials with a speed limit of 45 mph or higher, and 10 roads with a speed limit of 40 mph or less. Of these 55 sites, 48 had paint markings and 7 had epoxy markings. The markings at these sites were subsequently replaced with a combination of epoxy, methyl methacrylate, polyester, tape, and thermoplastic markings with higher retroreflectivity. The researchers that performed the unpublished study analyzed 10,312 crashes and attempted to quantify exposure to wet conditions using available weather data. The analysis showed a statistically significant reduction of 11 percent in dry nighttime crashes when the older markings were replaced, but it showed a non-significant increase of 15 percent during wet conditions.

A 2001 VTRC study also examined whether restriping resulted in safety improvements.[16] A before and after study design with comparison sites was used to analyze data at 22 locations. An average of 2.5 years was available for both the before and after periods. The comparison variables in this analysis were daytime crashes at the site. This was done since all markings should be equally visible during the daytime. These sites represented a mixture of cases where the marking material in the before period was paint or thermoplastic. The marking material in the after period comprised a variety of marking options, including restriping with paint, thermoplastic, or waffle tape. In some cases, roads were also resurfaced and/or SRPMs were installed. The results of the analysis showed that there were statistically significant reductions in overall crashes for two cases:

1. when existing paint was replaced with new paint and SRPMs
2. when existing paint was replaced with thermoplastic and SRPMs.

The estimated reductions in crashes for the two scenarios were 51 percent and 75 percent, respectively. These results were based on only two and three sites, respectively, so these results may not be representative of studies that used larger sample sizes.

Summary of Literature Review

The literature review revealed several key findings that have direct relevance to the current study:

- States have differing practices with regard to where they install RPMs and how they maintain RPMs. The MUTCD offers general guidance, but states have significant latitude.

- Cost and durability data exist for the more commonly used marking materials. No durability data exist for many of the newer wet reflective marking materials, making life cycle cost analysis difficult.

- SRPMs or RPMs were consistently found to have the longest visibility distance of all materials studied. Wet reflective markings performed the best of the continuous marking systems, but RPMs were found to be visible from substantially longer distances.

- There is solid evidence that RPMs improve safety for only certain traffic/geometric conditions on two-lane roads and four-lane limited access freeways. No broad data exist for other facility types.

- No conclusive link between marking retroreflectivity and crash reductions has been shown, principally because of the difficulty of gathering a high-quality set of retroreflectivity data across a wide spectrum of roads.

As a result, there does not appear to be sufficient data available to quantify fully the potential cost or safety impacts of new wet reflective marking materials.

Visibility of Marking Materials

As discussed in the "Methods" section, the visibility data available from the literature review were assessed to determine the marking preview times that would be available to drivers at different posted speed limits. Table 21 summarizes the available preview times for the different marking materials that were evaluated under wet night conditions. RPMs consistently provided the longest preview times under wet conditions.

Several requirements for preview time are documented in the literature. The *Handbook* recommends that pavement markings be visible between 2 and 3 sec.[3] A 3.65-sec preview time was recommended by several researchers and implemented in several computer visibility models.[28] Table 22 shows the materials that met preview times ranging from 2 to 3.65 sec between 45 and 65 mph. Materials with preview times that exceeded 2.5 sec are also shown since 2.5 sec is the default value for stopping sight distance used by the AASHTO *Policy on the Geometric Design of Highways and Streets.*[29]

Table 22 shows that very few materials met the more conservative preview time thresholds. Only RPMs met the 3.65-sec threshold for 55 and 65 mph facilities. Wet reflective tape met the 3-sec preview time threshold at 55 mph and the 3.65-sec preview time threshold at 45 mph.

Table 21. Preview Times for Different Markings under Wet Conditions According to Studies in the Literature Review

Material	Range of Wet Visibility (ft)	Preview Time at Different Speeds (sec)		
		45 mph	55 mph	65 mph
RPMs	415-654	6.29-9.91	5.14-8.11	4.35-6.86
Paint with standard beads	73-185	1.11-2.80	0.90-2.29	0.77-1.94
Paint with large beads	88-192	1.33-2.91	1.09-2.38	0.92-2.01
Profiled thermoplastic	142-228	2.15-3.45	1.76-2.83	1.49-2.39
Wet reflective tape	222-280	3.36-4.24	2.75-3.47	2.33-2.94
Patterned tape	143.3-240	2.17-3.64	1.78-2.98	1.50-2.52
Polyurea with bead clusters	174-240	2.64-3.64	2.16-2.98	1.83-2.52
Epoxy with Visionglow and standard beads	178-220	2.70-3.33	2.21-2.73	1.87-2.31
Yellow methyl methacrylate	188-218	2.85-3.30	2.33-2.70	1.97-2.29
Rumble stripes with thermoplastic	160-200	2.42-3.03	1.98-2.48	1.68-2.10

Table 22. Preview Time Thresholds for Different Marking Materials at Different Driver Speeds Based on Wet Visibility Distances Reported by Studies in the Literature Review

Preview Time (sec)	45 mph	55 mph	65 mph
>2	All materials	All materials	All materials except paint with standard beads
>2.5	All materials	All materials except paint and rumble stripes	RPMs, wet reflective tape, patterned tape, polyurea with bead clusters
>3	All materials except paint with standard or large beads	RPMs, wet reflective tape	RPMs
>3.65	RPMs, wet reflective tape	RPMs	RPMs

Current VDOT Unit Costs for Pavement Marking Materials

The VDOT BidTab system was used to collect information on bid prices for pavement markings for projects let in 2006 and 2007. These unit costs bids are shown in Table 23. There were no bids in these years for Type B, Class II (polyester) longitudinal markings. In some cases, pavement markings were bid as one component of a much larger project, so sometimes the successful bid unit costs are actually higher than the average of all bids. In those cases, other aspects of the bid justified the ultimate selection of the contractor. The unit costs were generally comparable to those in the literature.

As discussed in the "Methods" section, on March 7, 2008, VDOT hosted a conference call regarding pavement markings with several other states. One of the items discussed during the call was the performance of wet reflective tape. Missouri and Texas had experiences with the material. Texas reported that the tape lost its retroreflectivity under wet night conditions after about 6 months. Missouri reported that they required a dry initial retroreflectivity of 500 $mcd/m^2/lux$. The 3M 380iWR tape was required to have a level of 200 $mcd/m^2/lux$ at 2 years and 100 $mcd/m^2/lux$ at 3 and 4 years. In addition, 95 percent of the tape had to be present at the site. They reported a cost of $4.40/lf for 6-in tape and $5.10/lf for 8-in contrast tape.

Table 23. VDOT Unit Costs for Selected Pavement Marking Materials in Bids for Projects Let in 2006 and 2007

Marking Type	Width (in)	Total Quantity Let	Unit Cost (All Bids)		Unit Cost (Successful Bids)	
			No. of Bids	Average	No. of Bids	Average
Type A marking (paint)	4	22,282.6 mi	349	$0.05/lf	143	$0.05/lf
	6	55.1 mi	13	$0.15/lf	5	$0.12/lf
Type B, Class I marking (thermoplastic)	4	1,710.9 mi	316	$0.42/lf	140	$0.40/lf
	6	111.9 mi	118	$0.72/lf	47	$0.73/lf
Type B, class III marking (epoxy)	4	1,530.3 mi	128	$0.38/lf	58	$0.37/lf
	6	362.1 mi	12	$0.34/lf	6	$0.31/lf
Type B, Class VI marking (Tape)	4	226.5 mi	117	$2.30/lf	49	$2.28/lf
	6	505.5 mi	66	$3.17/lf	32	$3.10/lf
Install SRPM	N/A	152,384	308	$23.26 ea.	138	$23.02 ea.
Replace SRPM Lens	N/A	35,179	22	$7.55 ea.	8	$6.38 ea.
Remove SRPM	N/A	10,161	17	$18.32 ea.	7	$18.57 ea.

The VDOT BidTab system was used to collect the unit cost information. There were no bids in these years for Type B, Class II (polyester) longitudinal markings. In some cases, pavement markings were bid as one component of a much larger project, so sometimes the successful bid unit costs were actually higher than the average of all bids. In those cases, other aspects of the bid justified the ultimate selection of the contractor.

Safety Benefits of Using SRPMs in Virginia

As discussed in the "Methods" section, the next major task was to assess the potential safety benefits of using SRPMs on roads in Virginia. NCHRP Report 518[5] provided robust methods to estimate the safety impacts of SRPMs for two types of facilities: two-lane roads and four-lane freeways. The models developed for those facilities could not be extrapolated to other types of roads.

The Highway Traffic Records Information System (HTRIS) roadway inventory was used to identify all roads in Virginia that were either two-lane roads or four-lane roads with access control. Crashes that occurred from 2005 through 2007 were gathered for these roads. Only crashes that occurred at night with no lighting were used in the analysis since SRPMs are not likely to create any significant benefit during the day or when highway lighting is present. Traffic volumes for these links were also obtained from the VDOT Traffic Monitoring System.

The earlier discussion of the results of NCHRP Report 518[5] showed that the models developed for two-lane roads and four-lane freeways differed. The two-lane model included factors for horizontal curvature and traffic volume, whereas the four-lane freeway model included only a traffic volume factor. As a result, different methodologies had to be applied to the two types of facilities. A number of assumptions had to be made in order to use the NCHRP Report 518 models since some of the data elements required (most notably horizontal curvature and SRPM presence) are not directly captured in VDOT databases. The assumptions used to perform this analysis, along with the results of the analysis, are discussed in the following sections.

Two-Lane Roads

VDOT's HTRIS roadway inventory database does not contain a specific data element that quantifies the horizontal curvature of a road, such as the degree of curvature or radius of curve. This represented a barrier to using the NCHRP Report 518 safety models for two-lane roads, since curvature is an explanatory variable in the model. As a result, it was necessary to try to identify some reasonable assumptions that could be applied so that the model could be extended to Virginia roads.

An earlier VTRC-funded project examined safety on two-lane primary and secondary roads.[30] In that research, detailed global positioning system (GPS) data were collected on 868.96 centerline miles of road at 105 sites around Virginia. The researchers then processed the GPS data to determine the curvature on the roads. That dataset showed that the following:

- Of the centerline miles on the primary system roads assessed, 15.4% had a degree of curvature greater than 3.5.

- Of the centerline miles on the secondary system roads assessed, 22.9% had a degree of curvature greater than 3.5.

The dataset did not show any significant differences in curvature by VDOT construction district, although this was likely because of the small number of samples once sites were separated by district.

The next task was to identify how often SRPMs were used on Virginia's primary and secondary systems. The VDOT's VisiWeb photo log was used to examine the 105 sites studied in the earlier VTRC project[30] to determine whether or not SRPMs were installed on the roads where GPS data were collected. That evaluation showed that SRPMs had been installed on 14.9 percent of the primary system centerline miles of the sites examined in that earlier study. SRPMs were not installed at any of the secondary road sites.

Next, all two-lane road segments on the primary and secondary system had to be identified. The HTRIS roadway inventory was queried to obtain this information. The shortest roadway segment evaluated in the earlier VTRC project was about 4 mi long, so all segments shorter than 4 mi were removed from further analysis. There was some concern that the curvature on those shorter segments might not be similar to the segments for which the GPS data that were collected in the earlier study. AADT data from 2005 through 2007 from the VDOT Traffic Monitoring System were then matched to the remaining segments of two-lane road. Any roads without valid traffic data were deleted from the analysis. Finally, HTRIS was used to identify the crashes that occurred during nighttime, unlighted conditions for each of the segments that remained for the years 2005 through 2007.

The subsequent steps assumed that the distribution of curvatures, the distribution of crashes, and the distribution of SRPMs were independent. This assumption was necessary given the lack of widespread GPS data and the significant work required to review the VisiWeb photo log for the entire secondary and primary system. The next step was to calculate an accident modification factor (AMF) to be applied to the two-lane roads. The AMF represents a multiplier that is applied to the observed number of crashes in order to estimate the number of crashes that would have occurred if SRPMs had been installed and is equivalent to θ from NCHRP Report 518.[5] Equation 3 shows how the AMFs were calculated. The equation is based on the NCHRP Report 518 crash models and essentially creates a weighted average θ depending on the percentage of roads without SRPMs and the percentage of centerline miles with a degree of curvature greater than 3.5. The proportion of road that already has SRPMs installed is assumed to have an AMF of 1.0, meaning that those sections of roads would be unaffected by a policy change toward requiring SRPMs.

$$\begin{aligned}\text{AMF} &= \%\text{Curve}\left[1(\text{RPMs}) + (1-\text{RPMs})(1.4309 - 0.1700\text{AADT2} - 0.4004\text{AADT3})\right] \\ &+ (1-\%\text{Curve})\left[1(\text{RPMs}) + (1-\text{RPMs})(1.1573 - 0.1700\text{AADT2} - 0.4004\text{AADT3})\right]\end{aligned} \quad \text{[Eq. 3]}$$

where

RPMs = % of centerline miles with RPMs
% Curve = % of centerline miles with a degree of curvature > 3.5
AADT2 = 1 if 5,000 < AADT ≤ 15,000, 0 otherwise
AADT3 = 1 if 15,000 < AADT ≤ 20,000, 0 otherwise.

Several assumptions were made in developing the AMF equations. They included the following:

- *Crashes are uniformly distributed over the length of the road.* This is a simplification, but the lack of state-level horizontal curvature data limited the ability to assume different distributions of crashes through horizontal curves. Ideally, specific sections of road where the degree of curvature is greater than 3.5 would be identified and crashes would be assigned to those sections. This cannot be done with the data currently available, however.

- *The percentage of centerline miles exceeding the 3.5 degree of curvature is the same across all districts.* The percentage of miles exceeding this threshold was assumed to be 15.4 and 22.9 for the primary and secondary system, respectively, as shown in the field data collected in the earlier VTRC study.[30]

- *The percentage of miles with SRPMs installed is 14.9 percent for the primary system and 0 percent for the secondary system*, as taken from the field data collected in the earlier VTRC study.

Using these assumptions, it was possible to calculate AMFs for two-lane roads on Virginia's primary and secondary systems based on the three AADT categories used in NCHRP Report 518.[5] Table 24 shows the results of this process. Using this methodology, it appears that only primary and secondary two-lane roads with AADTs above 15,000 vpd are likely to see safety benefits from the installation of SRPMs. These high-volume, two-lane roads represent only 1.1 percent of all of the two-lane roads analyzed. Thus, it appears that SRPMs are not expected to provide a safety benefit for most two-lane roads in the primary and secondary systems.

This analysis was limited by the lack of system-wide data on horizontal curvature and SRPM usage. There may be cases where SRPMs may generate safety benefits on lower volume roads, specifically those in the 5,000 vpd through 15,000 vpd range. The lack of data on roadway curvature makes it impossible to make this assessment, however.

Table 24. Safety Benefits of SRPMs on Two-Lane Primary and Two-Lane Secondary Roads in Virginia (2005-2007 Nighttime Crashes in Unlighted Conditions)

Road System	AADT	Centerline Miles of Road	No. of Actual Crashes	AMF	No. of Predicted Crashes with SRPMs	Predicted Crashes – Actual Crashes
Primary	<5,000	3437.55	4524	1.1696	5291.3	+767.3
	5,000-15,000	1016.43	2922	1.0250	2995.1	+73.1
	>15,000	62.8	386	0.8290	320.0	-66.0
Secondary	<5,000	7284.02	6891	1.2200	8407.0	+1516.0
	5,000-15,000	280.01	1320	1.0500	1386.0	+66.0
	>15,000	76.49	396	0.8196	324.6	-71.4

AADT = annual average daily traffic, AMF = accident modification factor.

Four-Lane Divided Highways with Access Control (Four-Lane Freeways)

The process for determining AMFs for four-lane freeways required many fewer assumptions than the two-lane road analysis. For the four-lane freeways, AADT is the only factor in determining the AMFs. All sections of four-lane divided road with access control were identified, and AADTs were matched to those segments. Once again, nighttime crashes that occurred during unlighted conditions were identified for these sections. The AMFs were calculated directly using the methodology in NCHRP Report 518. In this case, these freeways were all assumed to have SRPMs installed. As a result, the number of crashes that were predicted to have happened had SRPMs not been installed was determined by dividing the actual crashes by the AMF. The results of those calculations are shown in Table 25.

Table 25 indicates that positive benefits were achieved for four-lane freeways with at least 20,000 vpd (both directions combined). Slight increases in crashes were predicted for four-lane freeways that had a combined AADT less than 20,000, but those roads made up only about 16 percent of the centerline miles and 7.5 percent of crashes analyzed for four-lane freeways.

Table 25. Safety Benefits of Using SRPMs on Four-Lane Freeways on the Primary and Interstate Systems in Virginia (2005-2007 Nighttime Crashes in Unlighted Conditions)

Road System	AADT	Centerline Miles of Road	No. of Actual Crashes	AMF	No. of Predicted Crashes with SRPMs	Predicted Crashes – Actual Crashes
Primary	<20,000	158.32	284	1.131	251.1	-32.9
	20,000-60,000	145.24	435	0.938	463.8	+28.8
	>60,000	8.25	8	0.673	11.9	+3.9
Interstate	<20,000	57.26	143	1.131	126.4	-16.6
	20,000-60,000	659.1	4081	0.938	4350.7	+269.7
	>60,000	59.19	452	0.673	671.6	+219.6

AADT = annual average daily traffic, AMF = accident modification factor.

Proposed Guidelines for Use of SRPMs

Background

Guidelines for the use of SRPMs were developed based on the findings of the literature review and the safety analysis. Two principles were used to develop these guidelines:

1. SRPMs should be used in situations where they have been demonstrated to show a safety benefit.

2. SRPMs should be used in situations where they have been shown to be the only marking material that can provide adequate preview distance during dark, rainy conditions. This ensures that drivers can see far enough down the road to detect changes in horizontal and vertical alignment.

SRPMs may be allowed in other situations, subject to engineering judgment, provided they have not been shown to degrade safety in that specific situation. The proposed guidelines are separated into (1) guidelines for use and (2) guidelines for installation and maintenance. The usage guidelines include information on the layout and spacing of SRPMs as well as the locations where SRPMs should be considered for installation.

Usage Guidelines

Layout and Spacing of SRPMs

The layout and spacing guidelines in the VDOT *Road and Bridge Standards*[31] conform to the requirements of the MUTCD[2] and represent best practices. This research identified several areas where revisions to the VDOT standards may be appropriate, however, to improve guidance to the driver or reduce costs to VDOT. These proposed revisions also comply with the requirements of the MUTCD.

First, it may be desirable to provide more specific guidance on the use of SRPMs through curves. For two-lane roads, a variable SRPM spacing may be used depending on the degree of curve present. The spacings shown in Table 26 may be used, subject to engineering judgment.

Table 26. Proposed SRPM Spacing by Degree of Curve for Two-Lane Roads

Degree of Curve	Radius (ft)	Minimum SRPM Spacing
<3	>1,910	2N (80 ft)
3-15	382-1,910	N (40 ft)
>15	<382	N/2 (20 ft)

Second, the lateral location of SRPMs shown in the VDOT standards could be modified. For two-lane, two-way roads with no passing zones, only one SRPM could be used. The SRPM should be placed in the gap between the two lines, as shown in Figure 3. The current standard requires two SRPMs, one on the outside of each line. One SRPM is permitted by the MUTCD, and there are no data available showing any safety benefit of using two SRPMs instead of one. This could produce some economic savings to VDOT through reduced SRPM installation and maintenance costs. As of the writing of this report, efforts were underway to change this standard.

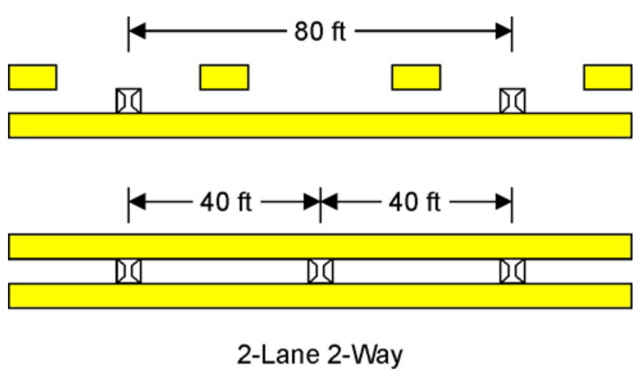

Figure 3. Recommended SRPM Layout

An exception to this layout would occur at locations where centerline rumble strips are present. In those instances, it is not feasible to place SRPMs between the yellow lines. Instead, SRPMs should be placed on the outside of both sides of the yellow line as outlined in VDOT Location and Design Instructional and Informational Memorandum IIM-LD-212.3. As a result, two SRPMs would be placed in a manner similar to that shown for the multilane undivided centerline in Figure 2.

Situations Where SRPMs Should Be Installed

Instituting the following requirements should be considered:

1. *SRPMs should be installed continuously on all two-lane, two-way roads where the AADT is greater than 15,000 vpd. If roadway lighting is present, engineering judgment should be used to determine whether SRPMs are still needed.*

    - *Justification.* NCHRP Report 518[5] safety models indicate consistent safety improvements on two-lane, two-way roads only at high volumes.

    - *Impact.* Based on segments at least 4 mi long, this guideline would impact only 62.8 centerline miles of the primary system and 76.49 miles of the secondary system. This accounts for only 0.8 percent of the centerline miles of the primary system and 0.2 percent of the secondary system. The roadway inventory data do not include information on the extent of street lighting, so fewer miles may be impacted.

2. *SRPMs should be installed continuously on all limited access highways with a posted speed limit of 55 mph or higher. SRPMs should also be installed on gore areas and the entrance/exit ramps of these facilities. This guideline applies even if roadway lighting is present.*

    - *Justification.* SRPMs provide an adequate wet night preview distance at these speeds. The NCHRP Report 518[5] models for four-lane freeways estimated that SRPMs create safety improvements on more than 80 percent of the centerline miles of four-lane freeways in Virginia. Field studies have also shown benefits in installing SRPMs on ramp entrance and exit ramps, as well as gore areas.

    - *Comments.* There are no field data to indicate whether SRPMs create measurable safety benefits on freeways with more than four lanes. SRPMs are recommended for these roads, however, to provide adequate preview time and to provide consistency on the interstate system. Even though the NCHRP Report 518 models suggest that SRPMs may degrade safety at volumes below 20,000 vpd, SRPMs should still be installed to provide adequate preview distance and consistency in marking among freeways.

- *Impact.* This requirement would impact the entire interstate system where no roadway lighting is present. It could also impact 311.81 centerline miles of the primary system (3.9 percent of the primary system).

3. *SRPMs should be installed continuously on all facilities with a posted speed limit of 60 mph or higher. If roadway lighting is present, engineering judgment should be used to determine whether SRPMs are still needed.*

   - *Justification*: SRPMs were the only marking material found to provide adequate preview distance at these high speeds. There are no field data available that predict safety improvements on these types of roads, however.

   - *Impact*: This requirement may impact 482.85 centerline miles of primary road that are not access controlled. The represents 6.0 percent of the primary system. The speed limits on these sections of road were increased to 60 or 65 mph since 2004 because of changes in the statutory maximum speed limits for certain highways.

For cases where an engineering study recommends that a speed limit be increased above the thresholds outlined here, SRPMs should be scheduled for installation the next time the road is resurfaced.

Situations Where SRPMs May Be Considered for Installation

SRPMs should be considered optional in the following two situations. SRPMs may be installed if additional delineation is determined to be needed.

1. *SRPMs may be considered for continuous installation on two-lane, two-way roads with AADTs from 5,000 through 15,000 if the sections have few horizontal curves with a degree of curvature greater than 3.5. If roadway lighting is present, engineering judgment should be used to determine whether SRPMs are still needed.*

   - *Justification.* SRPMs may generate modest safety improvements on roads with AADTs from 5,000 through 10,000 if they have few horizontal curves.

2. *SRPMs may be considered for continuous installation on multilane roads if the AADT is greater than 10,000 vpd and the speed limit is 45 mph or greater. If roadway lighting is present, engineering judgment should be used to determine whether SRPMs are still needed.*

   - *Justification.* SRPMs provide adequate preview time at these speeds. There are no field data, however, that indicate installation of SRPMs will improve safety on multilane divided or undivided roads with no access control or partial access control. The volume threshold is derived from thresholds used by South Carolina, West Virginia, and Illinois.[4,5] Less restrictive thresholds of 3,000 and 6,000 vpd are used in Kansas and Indiana, respectively, and could also be considered as alternative AADT thresholds.[4,5]

SRPMS should not be installed continuously in situations that are not explicitly mentioned. They may be considered for spot treatments, however, based on engineering judgment.

Maintenance and Inspection Guidelines

The literature shows a consensus that SRPM lenses have a service life of 2 to 4 years. The Indiana approach of replacing lenses on higher volume roads more frequently than lower volume roads[5] seems to be reasonable, given that past experience in Virginia has indicated that traffic volume plays a role in the service life of the lenses. A proposed lens replacement cycle is shown in Table 27. Thus, all lenses in SRPMs would be replaced on this cycle.

During the lens replacement process, crews should also inspect the condition of the SRPM castings. Any castings that are missing, cracked, or otherwise damaged should also be scheduled for removal and replacement. Given that casting life has been estimated at between 4 and 10 years, the lens replacement process timeline should be adequate for identifying any SRPM castings in need of replacement.

Table 27. Proposed SPRM Lens Replacement Cycle

Bi-directional Average Daily Traffic	Replacement Cycle (yr)
<15,000	3
≥15,000	2

Economic Analysis of Marking Systems

Preliminary Considerations for Economic Analysis

Based on the available data from the literature and the safety analysis in Virginia, several preliminary conclusions on SRPM usage can be made:

- SRPMs are the only marking that satisfy conservative requirements for preview time at driver speeds of 55 mph or greater.
- SRPMs are estimated to provide consistent safety benefits only on two-lane, two-way facilities with AADTs greater than 15,000.
- SRPMs are estimated to improve safety on four-lane freeways with AADTs greater than 20,000.

Several gaps in the knowledge base are also apparent:

- No data exist on the service life of many newer marking materials.

- No data exist on the potential crash reduction effects of many newer marking materials.

- No field data exist on the potential safety impacts of SRPMs on multilane arterial roads with no access control or freeways with more than four lanes.

As a result, it is impossible to perform a comprehensive cost/benefit analysis of the impacts of using different marking strategies across the entire road system maintained by VDOT. It is possible, however, to quantify some of the costs associated with installing and maintaining different marking systems using typical service lives and costs. Some benefits can also be quantified as a result of crash reductions on two-lane roads and four-lane freeways.

Cost Impacts of Alternative Lane Marking Options

The findings summarized in this report are data of the sort that the highway owner agency (VDOT, in this case) requires to solve cost minimization problems. In this particular problem, the agency chooses the values of certain decision variables that are under its control in order to minimize the cost outcomes that depend, in part, on those decisions.

The decision variables would appear to include the following:

- the choice among pavement marking types
- the choice of guidelines for location and spacing
- the use, or not, of quality or end-result specifications in the installation contract
- the use, or not, of a performance warranty in the installation contract
- the length of the inspection cycle
- the replacement criteria.

The cost outcomes would appear to include the following:

- the impact on agency costs (i.e., installation and maintenance costs)
- the impact on safety (i.e., crash costs)
- the impact on mean speed (i.e., delay costs created by marking operations).

The literature provides fairly specific estimates of some of the cost impacts of some of VDOT's choices. In other cases, the literature suggests the qualitative direction of the impacts but does not marshal enough information to permit numerical estimates. In a few cases, the absence of findings in the literature to date makes it impossible to say much about the impacts.

The bulk of this study bears on the cost consequences of choosing a given pavement marking system, and in particular on the cost consequences of choosing SRPMs as a supplementary marking system. As the MUTCD leaves the use of SRPMs to the discretion of state highway agencies[2], the identification of locations where SRPMs will bring about incremental net cost savings, when installed in combination with a continuous marking system, is a critical question for VDOT. The limited choice among permissible spacing intervals is of secondary importance.

Choice Among Marking Systems

Tables 11, 12, and 23 present some of the available information concerning agency costs of installation for various continuous marking systems (solid lines and skip lines) and for SRPMs. As noted earlier, research efforts to establish the relationship between detection distance or retroreflectivity on the one hand and crash rates on the other generally have failed to produce statistically significant results. Presumably, detection distance and recognition distance affect how fast motorists will choose to drive and how much time they will have to react to changes in curvature. Tables 13 through 20 compare detection distances and retroreflectivity for some of the available pavement marking systems. Tables 21 and 22 recast the detection distance findings in terms of preview time.

Choice of Location

The number of locations where SRPMs are installed will have an obvious straightforward impact on the installation cost to the agency. The impact on maintenance cost to the agency and the impacts on crash costs and travel time costs to the public will vary depending on the traffic volumes at the selected locations. The impact on crash costs will also depend on the geometrics at the selected locations.

As noted earlier, all surveyed state DOTs that reported using RPMs installed them non-selectively on the interstate system.[5] Tables 4 and 5 show further the installation (location) guidelines that certain states have followed for non-interstate highways. The guidelines in most of these states plainly reflect the expectation that RPMs will bring greater benefits, principally crash cost savings, on highway segments with high traffic volumes and on segments that have appreciable horizontal curves.

Safety benefits of SRPMs are likely to vary depending on where they are installed. As noted previously, one study had two findings concerning the safety impact of RPMs: (1) they significantly reduced erratic maneuvers near painted gores at interchange exits and bifurcations, and (2) they improved delineation.[26] Equations 1 and 2 summarized the statistically estimated crash reduction impact of SRPMs, controlling for traffic volumes and horizontal curvature, on two-lane roads and four-lane freeways from another study.[5]

Spacing

The guidelines in the MUTCD[2] establish the spacing of skip lines and thus limit the highway agency's freedom in choosing the spacing of RPMs. Tables 1 and 2 show the MUTCD guidelines for spacing RPMs. Table 3 shows the practices that certain individual states have followed. To the extent that the agency does have discretion to choose one RPM spacing or another, the impact of its choice on agency cost is straightforward. The rules shown in the tables reflect some expectation that closer-spaced SRPMs will bring greater benefits, principally crash cost savings, on curved highway segments. No data exist that could distinguish the impacts of different SRPM spacings on crashes or on mean speed, however.

Use of Quality or End-Result Specifications

In contracting for pavement and for concrete bridge components, VDOT has dealt with quality issues that are similar, in the sense that the quality of the product at the time of delivery has a quantifiable impact on the service life of the product. Among the tools VDOT has employed recently to address these issues are quality specifications, also called end-result specifications or performance specifications. The preliminary results have been encouraging.

Sprinkel, in 2004, describing VDOT's first experience with the use of a performance specification for the construction and acceptance of a high-performance concrete bridge overlay, concluded that the presence of the performance specifications, in place of the standard prescriptive specifications, likely influenced the contractor's decisions in ways that yielded a more durable product.[32] Even with the 6 percent pay adjustment paid to the contractor, the up-front cost remained below the average unit cost of an overlay in that construction district.

Hughes and Ozyildirim, extending the experimentation with end-result specifications to include other concrete bridge elements, noted specifically that "the mixture designed by the producer [for one of the pilot projects] would not meet the current [method-based] specifications but did produce a very good quality concrete under the special provision."[33] They also concluded, on the other hand, that although the end-result specifications adequately addressed some of the dimensions of concrete quality (compressive strength and permeability), some other important dimensions of quality (smoothness, cover depth, and thickness) "were difficult to evaluate by this approach mainly because of the difficulty in performing randomized testing."

McGhee and Gillespie found in 2006 that a rideability specification, i.e., a pay adjustment based on roughness, added about 2 percent to the up-front cost of an asphalt pavement resurfacing contract, and the resulting life-cycle cost benefit to the agency equaled from 3 to 4 percent of the up-front cost.[34] Hughes et al. in 2007 simulated an application of statistical quality assurance (SQA) specifications for hot-mix asphalt using sampling and testing results from real historical projects.[35] The researchers reported a general observation:

> The pay factor adjustments were caused by the average being too close to the lower specification limit, not by the variability component of PWL [percent within limits]. This indicates that Virginia's contractors should not be overly concerned about having to reduce variability but should instead place more attention on selecting the correct target.

In other words, the contractors appeared to have good control over their processes and to be able to achieve what they aimed to achieve.

VDOT experience to date suggests that a modification of the contract specifications to provide for pay adjustments based on measurable end results could be a valuable supplement to existing training conducted by VDOT's Materials Division. Although the use of such specifications requires that VDOT meet the technical challenges of measuring the "quality" that they want, quality specifications could elicit higher quality at installation and, as a consequence, greater life-cycle benefits.

Use of a Performance Warranty

The Vermont Agency of Transportation in its study of lens damage also found variability among brands (see Table 10).[15] It is plausible to ask whether a warranty, by encouraging contractors to take known differences in durability into account, could elicit greater life-cycle benefits. VDOT has experimented with warranties in contracts for pavement resurfacing. Diefenderfer and Bryant, reviewing the literature on pavement warranties in 2005, found sparse but encouraging evidence that warranties reduce the life cycle cost of a pavement.[36] They conservatively recommended further experimentation with warranties, and they also recommended that VDOT develop "a set of materials and workmanship specifications," i.e., quality specifications. They went further to suggest that "[t]his may achieve the same desired outcome of the warranty process without the need for future performance monitoring." The previous remarks about the potential impact of a quality specification on installation and maintenance costs to the agency, and on travel time and crash costs to the public, would apply also to the impact of a warranty.

Choice of Inspection Frequency and Replacement Criteria

If the number of functioning SRPMs on a highway segment were graphed versus time, a "sawtooth" shape would be expected, with the peak of each "tooth" on the graph representing a point in time when missing or damaged lenses and castings were replaced. As SRPMs may be supposed to suffer mostly from contact with tires rather than from environmental damage, the slope of each sawtooth will be relatively steep if the volume of traffic on the segment is relatively high. Other things being equal, a choice of inspection frequency and replacement criteria that makes replacement occur frequently would mean a higher average number of functioning SRPMs. A marginal increase in replacement frequency would presumably occasion a marginal increase in maintenance (replacement) costs and in the travel time costs because of the road work and a marginal decrease in crash costs attributable to the higher average number of functioning SRPMs.

The literature review discussed the inspection and replacement rules that certain state DOTs followed as of 1994[3] or as of 2004.[5] It should be noted that the Indiana replacement rules in Table 6 reflect the expectation that the rate of damage will be higher on roads where the volume of traffic is higher.

Benefit and Cost Comparison of Pavement Marking Options

The life-cycle costs of those pavement marking options for which the available data permit estimation are presented here. Agency costs account for the bulk of these costs. Travel time costs account for a small portion of the costs, attributable to the negative influence of work zones on traffic flow during restriping or SRPM replacement. Estimates of the life-cycle benefits of SRPMs on selected facilities are also presented, with crash cost savings accounting for the bulk of these benefits.

Costs of Pavement Markings

The highway agency has obviously a variety of pavement markings types from which to choose. Some pairs of choices, e.g., some kind of SRPM plus some kind of skip line, are not mutually exclusive. However, the cost of each marking system as a stand-alone proposition is presented, ignoring any cost synergies that might arise from simultaneous installation or simultaneous replacement.

The computation of the road user cost attributable to lane closures relies on the delay costs estimated in 2001 by Cottrell and Hanson.[16] Table 28 shows the total vehicle delay that is estimated to occur per hour of marking operations as a function of the number of lanes and the hourly volume on the highway.

The cost of maintenance of traffic (MOT) is another potential issue for marking operations. Marking operations typically require the use of several shadow vehicles, numerous personnel, and other traffic control devices. The exact nature of MOT requirements can vary considerably from site to site. Quantifying MOT costs is even more problematic that quantifying user delay costs since there are economies of scale depending on the length of the pavement marking operation and whether other work activities are being done concurrently with the marking operation. Given these difficulties, MOT costs were not explicitly included in the cost analysis of different marking systems.

Table 29 combines the service life data from Tables 7 and 11 with the unit cost data from Tables 12 and 23 to produce estimates of the annual cost of several of the pavement marking systems reviewed earlier. Only the most recent costs, those in Carlson et al. (2007)[19] and those found in the 2006-7 VDOT BidTabs, were used. For each system, a low-, middle-, and high-end service life is given, and a low-, middle-, and high-end unit cost is given where possible. The middle annual cost estimate is the ratio of the middle unit cost to the middle service life; the low annual cost estimate is either the ratio of the low unit cost to the middle service life or the ratio of the middle unit cost to the high service life, whichever is lower. The high annual cost estimate is either the ratio of the high annual cost to the middle service life or the ratio of the middle annual cost to the low service life, whichever is higher. With the exception of SRPMs, all of the systems reviewed in Table 29 are continuous markings that are assumed to be installed at the same speed in the same number of passes, so the choice among these systems would have no effect on travel time costs attributable to installation.

Table 28. Estimated Total Vehicle Delay for Marking Operations

No. of Lanes (Both Directions Combined)	Hourly Volume	Total Vehicle Delay per Hour (hr)
2	500	3.9
	1,000	16.3
	2,000	35.0
4	2,000	1.6
	4,000	22.5
6	3,000	0.6
	6,000	30.3

Source: Cottrell, B., and R. Hanson. *Determining the Effectiveness of Pavement Marking Materials*. VTRC 01-R9. Virginia Transportation Research Council, Charlottesville, 2001.

Table 29. Annual Costs of Selected Pavement Marking Systems

Material/Width of Marking	Annual Cost ($/mi-yr)			Service Life (yr)			Unit Cost ($/mi)		
	Low	Middle	High	Low	Middle	High	Low	Middle	High
Waterborne paint, 4 in	$83	$264	$1,056	0.25	1	3.17	$264	$264	$422
Waterborne paint, 6 in	$225	$713	$2,851	0.25	1	3.17	$634	$713	$792
Thermoplastic, 4 in	$422	$726	$3,249	0.65	2.91	5	$1,426	$2,112	$2,218
Thermoplastic, 6 in	$766	$1,315	$5,889	0.65	2.91	5	$3,802	$3,828	$3,854
Epoxy paint, 4 in	$604	$990	$1,980	1	2	3.28	$1,954	$1,980	$2,006
Epoxy paint, 6 in	$523	$858	$1,716	1	2	3.28	$1,637	$1,716	$1,795
Preformed tape, 4 in	$1,919	$4,714	$11,739	1.03	2.565	6.3	$12,038	$12,091	$12,144
Preformed tape, 6 in	$2,598	$6,381	$15,891	1.03	2.565	6.3	$14,520	$16,368	$19,800
Profiled thermoplastic	$853	$1,329	$2,640	1.5	2.98	4.64	--	$3,960	--
Methyl methacrylate	$1,901	$6,717	$10,560	0.9	1.415	5	$7,920	$9,504	$11,088
SRPM castings at 66/mi	$154	$192	$385	4	8	10	$1,519	$1,538	$1,558
SRPM lenses at 66/mi	$115	$153	$166	3	3	4	$421	$460	$498
SRPM total at 66/mi	$269	$346	$551						

The middle annual cost estimate is the ratio of the middle unit cost to the middle service life; the low annual cost estimate is either the ratio of the low unit cost to the middle service life or the ratio of the middle unit cost to the high service life, whichever is lower. The high annual cost estimate is either the ratio of the high annual cost to the middle service life or the ratio of the middle annual cost to the low service life, whichever is higher.

Tables 30 through 32 compute the costs of first-time installation of SRPMs, the costs of replacement of SRPM lenses, and the costs of replacement of SRPM castings plus lenses, including the removal of an existing SRPM. These costs are tabulated for only the sections of road where the proposed guidelines developed in this study recommended installation of SRPMs. These unit costs are used later to assess the annual costs of maintaining SRPMs. Tables 30 through 32 assume that:

- SRPMs are installed/replaced at 0.5 mph, and lenses are installed at 3 mph.
- The unit cost to install an SRPM is $23.26.
- The unit cost to replace an SRPM lens is $7.55.
- The unit cost to remove an old SRPM and replace it with a new one is $41.58.
- Road user costs are calculated assuming 1,000 vehicles/hour (vph) per lane for each facility type.
- The value of time to the driver is $15/hour.

Tables 33 through 35 compute the costs of installation of three continuous pavement markings: 6-in tape, 6-in thermoplastic, and 6-in wet night tape. The following assumptions were made in these calculations:

- A continuous double yellow centerline exists for two-lane, two-way roads.

- Markings are installed at 7 mph.

Table 30. SRPM Initial Installation Costs

Road Type	Length (mi)	SRPMs/ mi	DOT Cost ($/mi)	No. of Passes	Work Duration (hr/mi)	Delay (veh-hr/mi)	User Cost ($/mi)	Total Cost ($/mi)	Total Costs ($) by Facility Type		
									DOT Cost	User Cost	Total Cost
Primary/Secondary, 2-lane	139.29	66	1535.16	1	2	32.6	489.00	2024.16	$213,832	$68,113	$281,945
Primary/Secondary, 4-lane	482.85	132	3070.32	2	4	6.4	96.00	3166.32	$1,482,504	$46,354	$1,528,858
Primary, 4-lane, limited access	311.81	132	3070.32	2	4	6.4	96.00	3166.32	$957,356	$29,934	$987,290
Primary, 6-lane, limited access	11.56	264	6140.64	4	8	4.8	72.00	6212.64	$70,986	$832	$71,818
Interstate, 2-lane, 1 direction	1551.1	66	1535.16	1	2	3.2	48.00	1583.16	$2,381,187	$74,453	$2,455,639
Interstate, 3-lane, 1 direction	472	132	3070.32	2	4	2.4	36.00	3106.32	$1,449,191	$16,992	$1,466,183
Interstate, 4-lane, 1 direction	206.98	198	4605.48	3	6	3.6	54.00	4659.48	$953,242	$11,177	$964,419
Interstate, 5-lane, 1 direction	19.05	264	6140.64	4	8	4.8	72.00	6212.64	$116,979	$1,372	$118,351

DOT costs represent the material costs to install SRPMs but exclude maintenance of traffic costs. User costs are based on delays incurred under an assumed volume of 1,000 vph with a value of time of $15/hr.

Table 31. SRPM Lens Replacement Costs

Road Type	Length (mi)	SRPMs/ mi	DOT Cost ($/mi)	No. of Passes	Work Duration (hr/mi)	Delay (veh-hr/mi)	User Cost ($/mi)	Total Cost ($/mi)	Total Costs ($) by Facility Type		
									DOT Cost	User Cost	Total Cost
Primary/Secondary, 2-lane	139.29	66	498.3	1	0.33	5.43	81.50	579.8	$69,408	$11,352	$80,760
Primary/Secondary, 4-lane	482.85	132	996.6	2	0.67	1.07	16.00	1012.6	$481,208	$7,726	$488,934
Primary, 4-lane, limited access	311.81	132	996.6	2	0.67	1.07	16.00	1012.6	$310,750	$4,989	$315,739
Primary, 6-lane, limited access	11.56	264	1993.2	4	1.33	0.8	12.00	2005.2	$23,041	$139	$23,180
Interstate, 2-lane, 1 direction	1551.1	66	498.3	1	0.33	0.53	8.00	506.3	$772,913	$12,409	$785,322
Interstate, 3-lane, 1 direction	472	132	996.6	2	0.67	0.4	6.00	1002.6	$470,395	$2,832	$473,227
Interstate, 4-lane, 1 direction	206.98	198	1494.9	3	1	0.6	9.00	1503.9	$309,414	$1,863	$311,277
Interstate, 5-lane, 1 direction	19.05	264	1993.2	4	1.33	0.8	12.00	2005.2	$37,970	$229	$38,199

DOT costs represent the material costs to replace SRPM lenses but exclude maintenance of traffic costs. User costs are based on delays incurred under an assumed volume of 1,000 vph with a value of time of $15/hr.

Table 32. Costs to Remove Old SRPM Installation and Replace with New SRPM

Road Type	Length (mi)	SRPMs/ mi	DOT Cost ($/mi)	No. of Passes	Work Duration (hr/mi)	Delay (veh-hr/mi)	User Cost ($/mi)	Total Cost ($/mi)	Total Costs by Facility Type ($)		
									DOT Cost	User Cost	Total Cost
Primary/Secondary, 2-lane	139.29	66	2744.28	1	2	32.6	489.00	3233.28	$382,251	$68,113	$450,364
Primary/Secondary, 4-lane	482.85	132	5488.56	2	4	6.4	96.00	5584.56	$2,650,151	$46,354	$2,696,505
Primary, 4-lane, limited access	311.81	132	5488.56	2	4	6.4	96.00	5584.56	$1,711,388	$29,934	$1,741,322
Primary, 6-lane, limited access	11.56	264	10977.12	4	8	4.8	72.00	11049.1	$126,896	$832	$127,728
Interstate, 2-lane, 1 direction	1,551.1	66	2744.28	1	2	3.2	48.00	2792.28	$4,256,653	$74,453	$4,331,106
Interstate, 3-lane, 1 direction	472	132	5488.56	2	4	2.4	36.00	5524.56	$2,590,600	$16,992	$2,607,592
Interstate, 4-lane, 1 direction	206.98	198	8232.84	3	6	3.6	54.00	8286.84	$1,704,033	$11,177	$1,715,210
Interstate, 5-lane, 1 direction	19.05	264	10977.12	4	8	4.8	72.00	11049.1	$209,114	$1,372	$210,486

DOT costs represent the material costs to remove an old SRPM and replace it with a new one but exclude maintenance of traffic costs. User costs are based on delays incurred under an assumed volume of 1,000 vph with a value of time of $15/hr.

Table 33. Installation Costs for 6-Inch Tape

Road Type	Length (mi)	No. of Lines		DOT Cost ($/mi)	No. of Passes	Work Duration (hr/mi)	Delay (veh-hr/mi)	User Cost ($/mi)	Total Cost ($/mi)	Total Costs by Facility Type ($)		
		Solid	Skip							DOT Cost	User Cost	Total Cost
Primary/Secondary, 2-lane	139.29	4	0	66950	4	0.57	9.31	139.71	67090.1	$9,325,521	$19,461	$9,344,982
Primary/Secondary, 4-lane	482.85	4	2	75319	6	0.86	1.37	20.57	75339.8	$36,367,876	$9,933	$36,377,809
Primary, 4-lane, limited access	311.81	4	2	75319	6	0.86	1.37	20.57	75339.8	$23,485,280	$6,414	$23,491,694
Primary, 6-lane, limited access	11.56	4	4	83688	8	1.14	0.69	10.29	83698.3	$967,433	$119	$967,552
Interstate, 2-lane, 1 direction	1,551.1	2	1	37660	3	0.43	0.69	10.29	37669.9	$58,413,806	$15,954	$58,429,760
Interstate, 3-lane, 1 direction	472	2	2	41844	4	0.57	0.34	5.14	41849.1	$19,750,368	$2,427	$19,752,795
Interstate, 4-lane, 1 direction	206.98	2	3	46028	5	0.71	0.43	6.43	46034.8	$9,526,958	$1,331	$9,528,289
Interstate, 5-lane, 1 direction	19.05	2	4	50213	6	0.86	0.51	7.71	50220.5	$956,554	$147	$956,701

DOT costs represent the material costs to install 6-in tape but exclude maintenance of traffic costs. User costs are based on delays incurred under an assumed volume of 1,000 vph with a value of time of $15/hr.

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Table 34. Installation Costs for 6-Inch Thermoplastic

Road Type	Length (mi)	No. of Lines		DOT Cost ($/mi)	No. of Passes	Work Duration (hr/mi)	Delay (veh-hr/mi)	User Cost ($/mi)	Total Cost ($/mi)	Total Costs by Facility Type ($)		
		Solid	Skip							DOT Cost	User Cost ($)	Total Cost ($)
Primary/Secondary, 2-lane	139.29	4	0	15206	4	0.57	9.31	139.71	15346.1	$2,118,099	$19,461	$2,137,560
Primary/Secondary, 4-lane	482.85	4	2	17107	6	0.86	1.37	20.57	17127.8	$8,260,212	$9,933	$8,270,144
Primary, 4-lane, limited access	311.81	4	2	17107	6	0.86	1.37	20.57	17127.8	$5,334,196	$6,414	$5,340,610
Primary, 6-lane, limited access	11.56	4	4	19008	8	1.14	0.69	10.29	19018.3	$219,732	$119	$219,851
Interstate, 2-lane, 1 direction	1551.1	2	1	8554	3	0.43	0.69	10.29	8563.89	$13,267,489	$15,954	$13,283,443
Interstate, 3-lane, 1 direction	472	2	2	9504	4	0.57	0.34	5.14	9509.14	$4,485,888	$2,427	$4,488,315
Interstate, 4-lane, 1 direction	206.98	2	3	10454	5	0.71	0.43	6.43	10460.8	$2,163,852	$1,331	$2,165,182
Interstate, 5-lane, 1 direction	19.05	2	4	11405	6	0.86	0.51	7.71	11412.5	$217,261	$147	$217,408

DOT costs represent the material costs to install 6-in thermoplastic but exclude maintenance of traffic costs. User costs are based on delays incurred under an assumed volume of 1,000 vph with a value of time of $15/hr.

Table 35. Installation Costs for 6-Inch Wet Night Tape

Road Type	Length (mi)	No. of Lines		DOT Cost ($/mi)	No. of Passes	Work Duration (hr/mi)	Delay (veh-hr/mi)	User Cost ($/mi)	Total Cost ($/mi)	Total Costs by Facility Type ($)		
		Solid	Skip							DOT Cost	User Cost ($)	Total Cost ($)
Primary/Secondary, 2-lane	139.29	4	0	92928	4	0.57	9.31	139.71	93067.7	$12,943,941	$19,461	$12,963,402
Primary/Secondary, 4-lane	482.85	4	2	104544	6	0.86	1.37	20.57	104565	$50,479,070	$9,933	$50,489,003
Primary, 4-lane, limited access	311.81	4	2	104544	6	0.86	1.37	20.57	104565	$32,597,865	$6,414	$32,604,279
Primary, 6-lane, limited access	11.56	4	4	116160	8	1.14	0.69	10.29	116170	$1,342,810	$119	$1,342,929
Interstate, 2-lane, 1 direction	1551.1	2	1	52272	3	0.43	0.69	10.29	52282.3	$81,079,099	$15,954	$81,095,053
Interstate, 3-lane, 1 direction	472	2	2	58080	4	0.57	0.34	5.14	58085.1	$27,413,760	$2,427	$27,416,187
Interstate, 4-lane, 1 direction	206.98	2	3	63888	5	0.71	0.43	6.43	63894.4	$13,223,538	$1,331	$13,224,869
Interstate, 5-lane, 1 direction	19.05	2	4	69696	6	0.86	0.51	7.71	69703.7	$1,327,709	$147	$1,327,856

DOT costs represent the material costs to install 6-in wet night tape but exclude maintenance of traffic costs. User costs are based on delays incurred under an assumed volume of 1,000 vph with a value of time of $15/hr.

- The unit costs for the different marking systems are as follows:

  — 6-in tape: $3.17/lf
  — 6-in thermoplastic: $0.72/lf
  — 6-in wet night tape: $4.40/lf.

- Road user costs are calculated assuming 1,000 vph per lane for each facility type.

- The value of time to the driver is $15/hr.

These costs were tabulated for only the sections of road where the proposed guidelines recommended SRPM installation. The entire VDOT system was not examined. Further, it should be emphasized that this represents just one set of traffic volume assumptions. User delays could be significant if volumes were much higher that those that were used here.

Table 36 shows the resulting annualized cost per mile of SRPMs on each type of highway based on the data in Tables 30 through 32. This analysis was based on the assumption that the service life of SRPM lenses is 3 years and the service life of SRPM castings is 8 years. The time horizon of the life cycle was set at 12 years, the assumed service life of the pavement riding surface. A 2 percent discount rate was assumed. Table 36 indicates a total annual cost of approximately $3.76 million to provide SRPMs on the recommended roads. It should be noted that this cost figure does not include maintenance of traffic or the cost of providing SRPMs on freeway ramps, gores, or turn lanes. Quantifying those costs would involve an effort that was beyond the scope of this project. Table 35 includes only the cost of providing SRPMs for lane delineation along centerlines and skip lines. As a result, the annual cost incurred by VDOT is likely to be higher.

Table 36. Annual Cost of Providing SRPMs by Road Type ($/mile/yr)

Road Type	Length (mi)	Annual Cost Total ($/mi-yr)	Total Annual Cost
Primary/Secondary, 2-lane	139.29	$882	$122,853.78
Primary/Secondary, 4-lane, not limited access	482.85	$1,512	$730,069.20
Primary, 4-lane, limited access	311.81	$1,512	$471,456.72
Primary, 6-lane, limited access	11.56	$2,989	$34,552.84
Interstate, 2-lane, 1 direction	1551.1	$756	$1,172,631.60
Interstate, 3-lane, 1 direction	472	$1,495	$705,640
Interstate, 4-lane, 1 direction	206.98	$2,242	$464,049.16
Interstate, 5-lane, 1 direction	19.05	$2,989	$56,940.45
Total annual cost			$3,758,193.75

Analysis assumes an SRPM lens service life of 3 years, an SRPM casting service life of 8 years, a pavement life cycle of 12 years, and a 2% discount rate. Costs are only for SRPMs supplementing skip lines and centerlines. Gore areas, turn lanes, and ramps are not included.

Benefits of SRPMs

This section presents estimates of the benefits of SRPMs as complements to a continuous pavement marking system. All relevant crash information reviewed in this study involved road segments where SRPMs are combined with a continuous pavement marking system. As noted earlier, the NCHRP Report 518 models[5] apply only to two-lane, two-way roads and four-lane limited access freeways. Benefits could not be estimated for other road configurations.

In order to translate safety benefits into dollar numbers, the estimated crash savings shown in Tables 24 and 25 must be broken down by severity. The VDOT HSIP defines dollar costs for different types of crashes, with varying values for PDO, injury, or fatal crashes. These represent costs borne by motorists, insurers, and property owners. The NCHRP Report 518 models[5] provide an estimate of the total number of crashes that would occur at a site if SRPMs were used, but they do not provide a breakdown by the severity of the crash. It was assumed that the severity of crashes prevented was identical with what was actually observed for nighttime, unlighted crashes for the roads evaluated. The crash severity distribution used is shown in Table 37. The percentages in Table 37 are derived directly from nighttime, unlighted crash data in Virginia from 2005 through 2007.

The VDOT crash database was then used to determine the relative proportion of injury crashes by severity. The occupant records were examined to determine the most severe injury that occurred in each crash for unlighted, nighttime crashes on each facility type. The crashes were categorized as follows:

- *Injury C:* coded as injury type 4 (no visible injury but complaint of pain)

- *Injury B:* coded as injury type 2 (visible signs of injury such as bleeding wounds, distorted member, or had to be carried from scene) with no medical transport or injury type 3 (other visible injury such as bruises, abrasions, swelling, or limping)

- *Injury A:* coded as injury type 2 and required medical transport.

The VDOT HSIP defines different crash costs for each of these injury severities, so it is important to estimate the proportion of injuries in each category. The distribution of injuries by type for each facility is shown in Table 38. Table 39 shows the estimated annual crash reductions for each roadway group shown in Tables 24 and 25 once the crash types have been disaggregated. There is no net safety benefit predicted for installing SRPMs on four-lane primaries with access control, even though the speeds on those roads would justify SRPM installation.

One assumption in the economic analysis is that the annual crash reductions are maintained throughout the analysis interval. Given that the AMFs are a function of traffic volume, AADTs would have to be predicted for each link in order to provide dynamic estimates of crash reductions over time. Given recent reductions in VMT, it was decided that there was

Table 37. Severity of Nighttime, Unlighted Crashes for Roads Evaluated in this Study (2005-2007) (%)

Road	Fatal	Injury	PDO
2-lane secondary	2.0%	32.4%	65.6%
2-lane primary	1.7%	37.0%	61.3%
4-lane primary with access control	2.6%	27.6%	69.7%
4-lane interstate with access control	1.6%	31.7%	66.7%

Table 38. Distribution of Injuries by Road Configuration Using Virginia Data

Road	Injury A	Injury B	Injury C
2-lane primary	44.30%	26.91%	28.75%
2-lane secondary	40.98%	32.21%	26.81%
4-lane interstate with access control	30.72%	18.77%	50.51%

Injury A = severe, incapacitating injury; Injury B = serious but non-incapacitating injury; Injury C = no visible injury, but complaint of pain.

Table 39. Estimated Annual Crash Reductions by Configuration Using Virginia Data

Road	Fatal	Injury A	Injury B	Injury C	PDO
2-lane primary	0.37	3.61	2.19	2.34	13.49
2-lane secondary	0.48	3.16	2.48	2.07	15.61
4-lane interstate with access control	2.52	15.35	9.38	25.23	105.12

Injury A = severe, incapacitating injury; Injury B = serious but non-incapacitating injury; Injury C = no visible injury, but complaint of pain; PDO = property damage only.

too much inherent uncertainty in long-term AADT trends to justify generating those projections. As a result, these annual crash reductions were assumed to remain constant over time. The researchers believed that this was a conservative, under-prediction of potential safety improvements generated by SRPMs.

Any computation of the benefits, i.e., the cost savings, of SRPMs depends on a set of debatable assumptions. The computations in this study relied on the most conservative possible set of assumptions. The benefits were assumed to arise from crash cost savings alone. The crash cost reduction was derived from the models published in NCHRP Report 518 and cited earlier in this report.[5] The available empirical findings have shown SRPMs to have a statistically significant positive impact on crashes only on two-lane roads and on four-lane limited access freeways. The crash reduction on roads where this impact has not been empirically proven was assumed to be zero.

Table 40 shows the computation of the average cost of a crash on each road type. The computation uses the crash severity percentages provided in Tables 38 and 39 (the injury percentages for four-lane interstates are applied also to four-lane limited access primary roads). It uses the crash cost estimates applied in the VDOT HSIP.[1]

Table 40. Average VDOT Crash Costs for Road Types Analyzed

Road Type	Length (mi)	Proportion of Crashes					Average Cost ($/crash)
		Fatal	Injury A	Injury B	Injury C	PDO	
Secondary, 2-lane	7640.6	0.02	0.133	0.104	0.087	0.656	$111,445
Primary, 2-lane	4516.8	0.017	0.164	0.100	0.106	0.613	$105,955
Primary, 4-lane, limited access	311.81	0.026	0.085	0.052	0.139	0.697	$123,920
Interstate, 2-lane, 1 direction	1551.1	0.016	0.097	0.060	0.160	0.667	$89,338

Injury A = severe, incapacitating injury; Injury B = serious but non-incapacitating injury; Injury C = no visible injury, but complaint of pain; PDO = property damage only.

Tables 41 and 42 present the estimated benefits side by side with the estimated costs for each roadway geometry. Table 41 compares the existing state of affairs with the state that would exist if the proposed guidelines developed in this study were implemented. As SRPMs are already installed on all interstate highways and on a limited number of segments of primary and secondary roads, the incremental cost and benefit in this comparison involve only approximately 76.49 miles of secondary road and approximately 53.44 miles of primary road. Under the proposed guidelines recommendations, SRPMs would also be removed from approximately 663.64 miles of lower volume primary road. The incremental cost of this change was taken to be zero, as the cost of removing the SRPMs before the next resurfacing is an unavoidable cost. It should be noted that Table 41 shows only additional costs to extend SRPMs to other parts of the system and does not quantify maintenance costs for the existing system. Table 42 compares a hypothetical "zero" baseline state, in which no roads have SRPMs, with the state that would exist if the proposed guidelines developed in this study were implemented. Table 42 is used to illustrate the benefit that installing SRPMs on high-speed limited access roads has already produced. This contains a full cost for installing and maintaining SRPMs on the entire roadway system where the proposed guidelines recommend SRPM usage.

Table 41 indicates that expansion of the use of SRPMs could result in a crash reduction benefit of more than $9.15 million annually. The annual cost to VDOT for this benefit is only about $96,000 per year. Furthermore, the analysis implies that there is a significant potential benefit in removing SRPMs from lower volume two-lane primary and secondary roads in terms of both crash reductions and lower ongoing maintenance costs. Table 42 indicates that the four lane limited access freeways are already accruing substantial benefits from having SRPMs installed. Continued investment in an installation and maintenance program at these sites appears to be worthwhile.

It should be noted again that this benefit/cost comparison applies only to two-lane non-limited-access roads and to four-lane limited-access roads, as benefit estimates were possible only for these geometries. The computed benefits and costs apply to SRPMs used to supplement 6-in tape. The benefits of SRPMs used to supplement another continuous marking system would presumably vary depending on the night visibility that the other system affords in the absence of SRPMs.

Alternative Assumptions

Other scenarios, incorporating different assumptions, are possible. One alternative scenario would make the assumption that SRPMs convey some crash reduction on roads other than two-lane roads and four-lane freeways. This impact, if real, would raise the benefit on four-lane non-limited-access highways from zero to some positive number; it would likewise raise the benefit on limited-access highways of more than four lanes from zero to some positive number. The justification for such a scenario would be the proven night visibility enhancement that SRPMs provide. This enhancement might have less of an impact on highways with more lanes, where drivers have more room for avoidance maneuvers and where roadway departure may be less likely than on two-lane roads and four-lane freeways, but the impact is probably not zero. However, no data exist that can be used to estimate those scenarios.

Table 41. Benefits Assessment: Existing System versus Proposed Guidelines

Road Type		Total Centerline Miles	Existing Centerline Miles with SRPMs (Estimated)	Recommended Centerline Miles with SRPMs	Projected Additional Total Cost ($/yr)	Projected Additional DOT Cost ($/yr)	2005-7 Crashes (Existing)	Projected Crashes (3 Years)	Projected Crash Savings ($/yr)
Secondary 2-lane	<15,000 ADT	7564.12	0	0	$0	$0	8211	8211	$0
	>15,000 ADT	76.49	0	76.49	$67,489	$56,770	396	325	$2,654,491
Primary 2-lane	<15,000 ADT	4453.98	663.64	0	$0	$0	7446	7328	$4,164,256
	>15,000 ADT	62.8	9.36	62.8	$47,151	$39,662	386	320	$2,331,511
Primary 4-lane limited access		311.81	311.81	311.81	$0	$0	727	727	$0
Interstate, 2-lane, 1 direction		1551.1	1551.1	1551.1	$0	$0	4676	4676	$0
Total					$114,640	$96,432			$9,150,258

ADT =average daily traffic.
This table compares the existing VDOT system to what would have been estimated to have occurred if the proposed guidelines had been in place from 2005 through 2007. Only roadways where valid crash models exist are examined. This table shows the incremental improvement of using the proposed guidelines versus the current situation.

Table 42. Benefits Assessment: Hypothetical No SRPM System versus Proposed Guidelines

Road Type		Total Centerline Miles	Existing Centerline Miles with SRPMs (Estimate)	Recommended Centerline Miles With SRPMs	Projected Additional Total Cost ($/yr)	Projected Additional DOT Cost ($/yr)	2005-7 Crashes (Existing)	Projected Crashes (3 Years)	Projected Crash Savings ($/yr)
Secondary 2-lane	<15,000 ADT	7564.12	0	0	$0	$0	8211	8211	$0
	>15,000 ADT	76.49	0	76.49	$67,489	$56,770	396	325	$2,654,491
Primary 2-lane	<15,000 ADT	4453.98	0	0	$0	$0	7328	7328	$0
	>15,000 ADT	62.8	0	62.8	$55,410	$46,609	401	320	$2,874,190
Primary 4-lane limited access		311.81	0	311.81	$471,418	$462,840	727	727	-$10,535
Interstate, 2-lane, 1 direction		1551.1	0	1551.1	$1,172,535	$1,151,199	5149	4676	$19,529,892
Total					$2,531,417	$2,468,460			$25,048,038

ADT =average daily traffic.
This table compares a hypothetical “no SRPM” case to what would have been estimated to have occurred if the proposed guidelines had been in place from 2005 through 2007. Only roadways where valid crash models exist are examined. This table provides an assessment of total costs and benefits for these roads.

Another possible alternative scenario would allow for the possibility that motorists capture some of the benefits of improved night visibility in the form of travel time reduction rather than crash reduction. This impact, if real, would imply a benefit attributable to travel time savings in addition to any crash cost savings. The justification for such a scenario would be the evidence, in some of the empirical studies to date, that drivers on the studied routes responded to an increase in night-time visibility distance by increasing their speed.

CONCLUSIONS

- *Based on the review of the literature, SRPMs still appear to be the only marking system that provides sufficient preview time to drivers at high speeds.*

- *Although new marking systems, such as wet reflective tape, seem to show promise, there are no data that suggest that they can replace SRPMs on high speed roadways at this time.* Since past research was reviewed, the findings in this report are limited by the availability of relevant data. As a result, several factors that could influence the use of SRPMs and other marking materials remain unknown. For example:

  — There was no service life information on newer wet reflective marking materials. Tests were usually done on materials that had not been subjected to extensive weathering. As a result, it is unclear how long those materials may sustain their wet reflective properties under traffic.

  — There was no information available on the safety impacts of newer wet reflective marking materials. As a result, crash impacts from using those materials cannot be estimated.

  — NCHRP Report 518[5] did not evaluate safety on a number of facilities, such as multilane roads without access control or freeways with more than four lanes. There were no objective safety data available that could be used to estimate the safety performance of SRPMs on those facilities.

- *Based on the data available, VDOT's continued investment in SRPMs appears to be justified based on crash reduction and driver preview distance requirements, although there are currently no data that can be used to determine potential crash reductions from using SRPMs on many types of roads.*

- *The proposed guidelines developed in this report represent what is currently known about the effectiveness of SRPMs and wet reflective markings.* Likewise, there is inherent uncertainty in predicting crashes, although the NCHRP Report 518 models appear to be constructed from a large dataset and are the best information currently available. The VDOT inventory lacked some of the data elements necessary to perform a true evaluation of the VDOT system, most notably SRPM presence and horizontal curvature. As a result, several assumptions and extrapolations had to be made to assess safety impacts of changes in SRPM installation policy.

RECOMMENDATIONS

1. *Prior to implementing any guidelines for the installation and maintenance of SRPMs, the Maintenance Division should ensure that there is a sustainable funding stream available for the inspection and maintenance of SRPMs.* This report estimates an annual funding commitment of approximately $3.76 million to maintain SRPMs for lane delineation on the recommended roadways. This does not include maintenance of traffic costs or the costs to provide SRPMs on gores, ramps, or turn lanes.

2. *VDOT's Traffic Engineering Division (TED) should develop guidelines for where SRPMs should be installed on the interstate, primary, and secondary road systems.* This study developed proposed guidelines with regard to locations where SRPMs have been proven to create benefits. Given current budgetary issues, VDOT should focus investments in SRPM installation and maintenance on the facilities identified in this study. VDOT's TED should also recommend revisions of VDOT's *Road and Bridge Standards* to VDOT's Location & Design Division to reduce future SRPM installations as outlined in this study.

3. *VDOT's Maintenance Division should revise the Maintenance Manual, with the assistance of VDOT's TED, to reflect appropriate guidance for the maintenance of SRPMs installed on roads in Virginia.* The proposed maintenance guidelines developed in this study can serve as a potential model inspection and maintenance program.

4. *VDOT's TED should formally assess the durability, retroreflectivity, and safety benefits of any new marking systems, such as wet reflective tape, used in Virginia.* The lack of objective data on service life, cost, and safety benefits in the literature makes it difficult to assess the effectiveness of these marking systems formally at this time.

5. *VDOT's Materials Division should continue to improve training on SRPM installation and assess if there is room for improvement in existing processes, including procurement. The Materials Division should also work to develop a standard reference document that could be used by inspectors to assess the quality of SRPM castings and reflectors.* The Materials Division has already made progress in this area, but further work to improve the consistency and accuracy of inspection of new and existing SRPM installations may be valuable. A document for inspectors that shows acceptable installations of SRPM castings and reflectors will be needed to implement a maintenance program. The Materials Division can work with SRPM manufacturers to develop such a document.

COSTS AND BENEFITS ASSESSMENT

Table 41, a comparison of the costs and benefits of SRPM deployment in Virginia in accordance with the recommendations in this study and the costs and benefits of SRPM deployment as it is today, shows the net impact of implementing the study recommendations. The net cost accrues in the form of additional agency expenditures to install, replace, and remove SRPMs and in the form of additional travel time for motorists during these agency activities.

This additional cost is estimated to be a little more than $114,000 per year, including delay costs to users. The net benefit accrues in the form of crash reductions, which are estimated to be $9.15 million per year. The benefit/cost ratio of this incremental change in VDOT policy is almost 80 to 1; the net benefit is more than $9.15 million per year.

Table 36 shows the estimated total annualized costs of SRPM deployment in accordance with the study recommendations, including the cost of existing SRPM installations. These costs, as noted previously, are about $3.76 million. The lack of applicable accident models makes it impossible to estimate the *benefits* of some existing installations. Table 42 compares the total costs and benefits of recommended SRPM deployment, including existing installations, on those road geometries for which applicable accident models are available. The benefit/cost ratio for this group is almost 10 to 1.

The benefits will accrue to the motoring public through the reduction in crashes created by the use of SRPMs. The costs of the SRPM program are principally incurred by VDOT, with road users incurring some delay costs.

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