Guidelines for the Use of Raised Pavement Markers

PUBLICATION NO. FHWA-RD-97-152

OCTOBER 1998

U.S. Department of Transportation
Federal Highway Administration

Research and Development
Turner-Fairbank Highway Research Center
6300 Georgetown Pike
McLean, VA 22101-2296

Technical Report Documentation Page

1. Report No. FHWA-RD-97-152	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle GUIDELINES FOR THE USE OF RAISED PAVEMENT MARKERS		5. Report Date 6. Performing Organization Code
7. Author(s) Grant, A.R. and Bloomfield, J.R.		8. Performing Organization Report No. 10. Work Unit No. (TRAIS) 3A6C-0052
9. Performing Organization Name and Address The University of Iowa Center for Computer Aided Design 208 Engineering Research Facility Iowa City, Iowa 52242		11. Contract or Grant No. DTFH61-94-C-00120 13. Type of Report and Period Covered Final Report March 1994 -
12. Sponsoring Agency Name and Address Office of Safety and Traffic Operations R&D Federal Highway Administration 6300 Georgetown Pike McLean, Virginia 22101-2296		14. Sponsoring Agency Code

15. Supplementary Notes

Contracting Officer's Technical Representative (COTR): Joseph Moyer, HSR-30; Ester Wagner, SAIC

16. Abstract:

The Manual on Uniform Traffic Control Devices (MUTCD, 1988) provides a general outline for how Raised Pavement Markers (RPMs) should be used, but more specific information is required in order to produce a set of guidelines that are usable by a field traffic engineer. The Roadway Delineation Practices Handbook, produced by the Federal Highway Administration in 1994, gives more detailed instruction for some areas of RPM use (e.g., spacing and placement) but it is incomplete and is not presented in a clear, unambiguous manner. The following document is based on an extensive survey of the literature. Guidelines are presented for the use of RPMs on U.S. highways, with the core recommendations being extracted from the Roadway Delineation Practices Handbook (1994) and the MUTCD (1988). The guidelines also include a number of additional recommendations based on the work of other researchers. Several future research issues are also suggested.

17. Key Words Human performance, raised pavement markers, human factors.		18. Distribution Statement No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 59	22. Price

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yards	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: Volumes greater than 1000 l shall be shown in m^3.				
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9 or (F-32)/1.8	Celcius temperature	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.71	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

* SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

(Revised September 1993)

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SECTION 1. INTRODUCTION

The Manual on Uniform Traffic Control Devices (MUTCD, 1988), provides a general outline for how Raised Pavement Markers (RPMs) should be used, but more specific information is required in order to produce a set of guidelines that are usable by a field traffic engineer.(1) The Roadway Delineation Practices Handbook, produced by the Federal Highway Administration (FHWA) in 1994, gives more detailed instruction for some areas of RPM use (e.g., spacing and placement) but it is incomplete and is not presented in a clear, unambiguous manner.(2) In the next section of this report, some recommendations will be made on the basis of information provided by these two sources, along with information accumulated from a variety of other sources. Several areas require further research before recommendations can be made, and are also discussed in this section.

Before moving on to recommendations, however, certain issues need to be clarified regarding research method and measurement of RPM performance so that experimental results can be more easily compared. After these issues are described, this introductory section will conclude with a discussion of driving performance and what is required to measure the proficiency of this performance, with specific reference to evaluating the use of RPMs as effective delineators.

THE RELATIONSHIP BETWEEN GUIDANCE INFORMATION AND GROSS DRIVING PERFORMANCE

The task of driving can be performed using low-, medium- or high-level processing. If the guidance information is limited (as it is for instance, when driving at night with rain or fog on a road with very poor delineation), the driver will use compensatory error tracking to maneuver the vehicle. According to Freedman, Staplin, Gilfillan, and Byrnes (1988), low-level maneuvering of a vehicle by error correction forces lower speeds, erratic movements and potentially unsafe driving. (3) When there is more guidance information available, the driver controls the vehicle by use of a steady pursuit mode. If guidance information is well supplied, the driver can anticipate upcoming events and use precognitive control to perform the required maneuvers. For the driver to have access to as much anticipatory information as possible, especially at night or with adverse weather conditions, long-range delineation is required. Long-range delineation is particularly useful to prepare the driver for upcoming changes in road geometry (e.g., approaching curves), road structure (e.g., gores, bifurcations, road narrowings), or required changes in driver speeds (e.g., at intersections, construction zones). Long-range delineation presents information to the driver when the perceptual process first begins. Shinar, McDowell and Rockwell (1977) demonstrated that the curve negotiation process perceptually begins well before the curve, at a preview distance of 2.5 to 3.5 s.[4] The Roadway Delineation Practices Handbook (1994) cites Freedman et al. as finding 2 and 3 s to be acceptable minimum preview distances for short and long ranges, respectively.[2,3] Allen et al. (1977) indicated that a 3- to 4-s preview distance is required in adverse weather conditions.[5] And Blaauw and Padmos (1982) use a more conservative 5-s preview distance to evaluate the performance of road delineation.[6] On the basis of these studies, short-range delineation should provide a minimum preview distance of 2 s, and long-range delineation should provide a minimum preview distance of 3-4 s.

Curve delineation with RPMs has been the focus of much research. It is important to ensure that the driver has as much information as possible about the most important part of the curve in a timely fashion. The curve-assessment process was shown in studies by Cohen and Studach (1977), McLean and Hoffman (1973) (cited in Fildes and Triggs, 1985) [7], and Shinar et al. [4] to start well in advance of the vehicle entering the curve (at least 100 m (327.9 ft) before); far delineation is therefore essential to provide anticipatory information. But before we can measure whether RPMs provide adequate long-range information for curve navigation, it is important to know how drivers maneuver through curves under optimal conditions.

DRIVER NAVIGATION OF CURVES

Several studies have investigated how drivers maneuver through curves. According to studies by Johnson (1984), Swenson (1985), and McLean (1983) (cited in Zador, Stein, Wright and Hall, 1987) [8] the actual path that drivers follow when traveling around a curve is not in the center of the lane. Many drivers tend to cut the sharpness of a corner by steering a straighter path around a curve; this is called curve lengthening. As shown in Figure 1a, for the right curve, the driver has shifted toward the centerline before entering the curve, and then shifts away from centerline as the vehicle travels through the curve. In contrast, Figure 1b shows that, for the left curve, the driver has shifted to the right edge before entering the curve, and then shifts toward the centerline as the vehicle travels through the curve. According to Zador et al., the benefit of the curve-lengthening strategy is that the driver can reduce the lateral acceleration through a curve and thereby reduce peak friction demand. However, the strategy may also bring vehicles closer to the roadway boundaries and reduce the driver's margin of safety.[8]

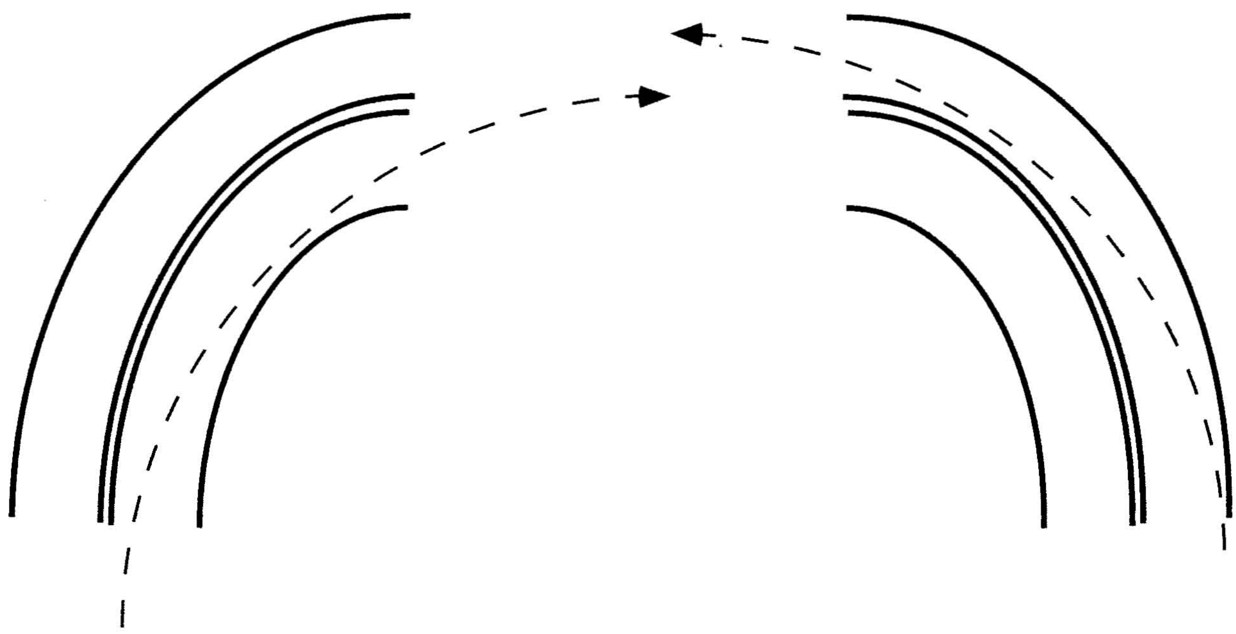

Figure 1. An example of the path taken by a vehicle when the corner-cutting strategy is used for maneuvering through (a) a right curve and (b) a left curve, on a two-lane, two-way road.

MEASURING DRIVER PERFORMANCE

Using Accident Analyses

As discussed by Pagano (1972), the use of accident information (e.g., rates and types) to determine the effects of highway improvements on driver performance can be time-consuming and has varying reliability, depending on several variables (e.g., season, weather, location, time of day, etc.).[(9)] The interpretation and comparison of accident data also require controlling for variables such as geographical region (e.g., avoid comparing urban areas with rural areas, predominantly hilly vs. flat areas etc.), type of accident (e.g., single-vehicle road departure accidents, head-on collisions, sideswipe collisions, rear-end collisions, etc.), source of accident (e.g., weather, delineation, driver impairment, obstruction, driver drowsiness, etc.), type of RPM used, or traffic speeds. It is difficult to determine whether delineation improvements are effective if studies do not account for these and other variables. For example, Bali, Potts, Fee and Taylor (1978) showed that, when RPMs were used to delineate the centerline, there was a lower accident rate than when it was delineated with paint.[(10)] A before-and-after study by Matthias (1988) indicated that the installation of retroreflective RPMs on the centerline appeared to have contributed to the 56-percent reduction in nighttime accidents along the study section.[11] However, the accident data collected by Nemeth et al. (1986) indicated that the addition of RPMs may not make a difference under all circumstances, especially where snow and ice are a problem.[12]

Using Performance Measures

Because of the concerns mentioned in the subsection above, driving performance measures such as vehicle speed, lateral position, and lane encroachments have been used to correlate driver behavior and accident rates, enabling researchers to measure changes in driving performance without having to rely on accident records. However, even if driving measures are predominantly used to determine driver performance, accident data will still be required to validate the results. The methodology used to gather and interpret accident data should therefore be thorough and consistent.

Pagano used performance measures to estimate the occurrence of different accident types.[9] For example, edgeline encroachments would be a factor in a model of single-vehicle road departure accidents, whereas encroachments of the centerline into the opposing lane would be a factor in a model of head-on collision or sideswipe accidents. Pagano collected data from nine sites (all of which were two-lane rural roads) to obtain some initial validation results, and according to his model the following correlation appeared to exist for horizontal curves: a strong correlation between accident rate and variance of lateral placement; some evidence that accident rates are correlated with deceleration rates; almost no correlation between accident rates and the variance in speed distributions; and negative correlation showing no support of the hypothesis that mean speed reductions will result in reduction in accident rates—in fact, it shows the reverse.[9]

With these and other driving measures, researchers have studied the effect of the use of RPMs on driver performance. According to Zador et al., several sources agree that decreases in the variability of speed and/or variability in lateral position of a vehicle are major benefits of improved curve delineation.[8] The sources include: Nedas and Luminello (1982) and Stimpson, McGee, Kittelson and Ruddy (1977) (cited by Zador et al.)[8]; and Taylor, McGee, Seguin, and Hostetter (1972)[13]. Variability appears to be the key element in assessing the driver's ability to control the vehicle; erratic maneuvers give the indication that the driver is using low-level processing to control vehicle maneuvers.[8,13] In some cases the notion of "center-is-best" or "slower is better" is used to describe good driving behavior (e.g., Krammes and Tyer, 1991[14] and Kallberg, 1993[15]). This evaluation of driver performance is not based on controlled versus noncontrolled driving, but rather on mean speed or actual position in lane, and may overlook the benefits of improved delineation. It also ignores the possibility that curve lengthening is desirable. Deceleration rates rather than mean speeds appear to be useful, and lane position relative to lanelines are useful in conjunction with variability measures. Lateral position reveals whether the driver crosses the lane boundaries (center/edgelines) and therefore could potentially have an accident. One potential disadvantage of using the curve-lengthening strategy to maneuver through curves is that the vehicle is driven closer to roadway boundaries. For instance, a study by Stimpson, Kittelson, and Berg (1977) revealed that, in the case of an isolated horizontal curve between the point of curvature and curve midpoint, the driver tended to move closer to the shoulder for the *inside curve* and closer to the centerline for the *outside curve*.[16] The accident model used in this study indicated that, as the magnitude and frequency of the displacement of the vehicle increases, the potential for either departure accidents or head-on collisions also seems to increase. However, if studies show less or no change in boundary encroachments (into the edgeline and/or centerline), then the frequency of accidents should be reduced, since safer, more controlled driving is performed by the driver.

EVIDENCE THAT RPMs IMPROVE DRIVER PERFORMANCE

On the basis of the previous information, it is assumed that the preferred driver behavior would entail using anticipatory information to maneuver the vehicle in a well-controlled manner. Driving measures would then show low variability for speed, deceleration rates through curves that would reflect advance warning, and a mean speed that is no greater than that achieved during clear-day conditions. The measure would indicate that the lateral position does not encroach onto the shoulder or adjacent lanes and there would be low variability in lateral position. If RPMs provide adequate long-range information, this should be reflected in the driving performance measures (e.g., deceleration rate and lateral control when maneuvering horizontal curves). As the following studies show, RPMs do in fact provide long-range information that produces more controlled driving.

Freedman et al. compared upgraded delineation (including RPMs with other far-delineation), which provided long-range information, with a baseline delineation scheme that provided short-range information.[3] Their results showed that the traffic speed tended to be more uniform (providing better traffic flow), that there was evidence of curve lengthening, and that drivers were less likely to use high beams and more likely to dim lights for opposing traffic with upgraded delineation. As was to be expected from curve lengthening, the frequency of near encroachments increased as the drivers hugged the centerline, but in spite of this, the frequency of centerline encroachments was significantly lower (by less than half).[3] It would be interesting to compare the results with a similar study using strictly RPMs as the upgraded delineator rather than RPMs in combination with other far-delineators. Earlier studies using RPMs show similar results. The experimental results of Allen et al. indicated that, when only striping was used for guidance, a dangerous combination of increasing lateral variability and decreasing mean distance from the lane-line occurred with many drivers over successive circuits on a highway. However, performance recovered when the driver returned to the road segment delineated with supplemental RPMs.[5] Zador et al. found that, when RPMs were used to delineate right curves (centerline with RPMs and painted edgelines), the drivers increased curve lengthening in day and night conditions.[8] When RPMs were used to delineate left curves (centerline with RPMs and painted edgelines), the drivers reduced curve lengthening at night, but increased curve lengthening in day conditions. Overall, Zador et al. concluded that there is strong evidence that supplemental delineation with RPMs effectively warns drivers of approaching curves.[8] It would be beneficial to have more information about how RPMs affect the number of boundary encroachments in curves in order to ensure that, by adding RPMs and increasing curve-lengthening behavior, the number of departure or side-swipe accidents does not also increase. For instance, Matthias found that, along with advantages of RPM retroreflective properties, the tactile and auditory warning provided by RPMs seemed to alert drivers to the crossing of the centerline during the day.[11] The before-and-after accident study found a reduction in the number of unsafe passing and road-departure accidents. Before the use of supplemental RPMs, eight accidents where a vehicle had inadvertently crossed the centerline occurred at night and seven accidents occurred during daylight hours, whereas only five accidents were reported at night and three accidents during the daylight hours in the after period.[11] As mentioned in the subsection referring to accident data, measuring the number of boundary encroachments—both incursions over the edgeline and the centerline—would give a more controlled estimate of how the use of RPMs might impact the potential of drivers to run off the road or encroach into the opposing lane.

Although it is evident that studies show RPMs to be beneficial, the advantages of better delineation should also balance with the driver's capability to respond to emergency situations at night. The use of RPMs may allow the driver to safely control the vehicle at higher speeds, but RPMs cannot provide the same advance information about an impending collision with a road hazard (e.g., an animal or person crossing the road). As discussed by Kallberg, successful steering and braking maneuvers are strongly speed-dependent, and given that detection distances are shorter at night than during the day, the driver requires more time to react to an impending collision.[15] Therefore, if the driver travels faster because far-delineation (in this study, post-mounted delineation) provides sufficient driving cues, there is a potential danger for hazard collisions to increase. According to the accident model used by Kallberg, the number of injury accidents in darkness could potentially increase by 40 to 60 percent.[15] This study should be considered when determining where RPMs should be used (e.g., perhaps RPMs should not be used on deer-crossing sections of winding mountain roads that have low levels of ambient lighting).

ISSUES TO OBSERVE

Although there are similarities in most studies investigating RPMs, there are enough differences to make it difficult to compare their research results. There are several approaches for accident analyses and for measuring driving performance. Required driver visibility distances used to evaluate RPM performance have not yet been established. It would also be very useful if common, consistent terminology was developed. These future research issues generated from the subsection above appear here within a box, as will other issues that are proposed throughout this document. The issues are numbered continuously and are compiled into a final list that is presented in section 4.

Future Research:

1. Future accident analyses should consider how variables such as road geometry, average daily traffic (ADT), and geographical region will affect the interpretation of results. Previous studies that have averaged over such variables should be re-evaluated.
2. Measurement of driving performance, including analyses of potential accidents because of curve lengthening when RPMs are used, should be investigated further.
3. Studies should report the driving situation that was investigated in terms specific to those set by FHWA guidelines. For example, if spacing specifications are described on the basis of the degree of curvature for horizontal curves, studies should report the road geometry in terms of degree of curvature. The reflectivity of RPMs should be measured in SI units and reported with reference to the minimum reflectivity criteria (yet to be established). These criteria along with required visibility distance should be used to evaluate RPM performance.

SECTION 2. RPM GUIDELINES[1]

The following section will present a collection of recommended practices along with future research issues, which can be used to complete an official set of guidelines for RPM use.

GENERAL DELINEATION REQUIREMENTS

Before discussing how RPMs should be used to delineate roadways, it is necessary to establish in general the type of delineation that is required by motorists.

- *Both center and edgelines are required to provide optimum driving performance.*
- *Centerlines should be supplemented with RPMs as recommended per road geometry.*
- *Edgelines should consist of a 152.4-mm (6-in) wide continuous stripe.*
- *Left edgelines should be supplemented by RPMs.*
- *Right edgelines should not normally be supplemented by RPMs, unless stated for specific road conditions or geometry.*
- *Edgelining should not be applied to roads narrower than 5.5 m (18 ft).*

Justification: Blaauw (1985) states that, although a centerline provides lateral vehicle control inside the lane, it does not provide sufficient preview information—edgelining is therefore required.(17) Good and Baxter (1986) found that continuous treatments were favored over discrete, and that wide edgelines were most beneficial to driver observation-control processes.(18) Freedman et al. found that edgelines on roadways greater than 6.1-m (20-ft) wide are recommended by several sources when they conducted a literature review. Although they found mixed results in research concerning overall accident reduction, a significant reduction in fatal and injury-producing accidents was found.(3) The MUTCD currently states that a normal width of a longitudinal line should be 101.6-mm (4-in) to 152-mm (6-in) wide (1986).(1) Pennell (1993) recommended that painted stripes (including edgelines) be applied with a 101.6-mm (4-in) width.(19) It has been noted by the Roadway Delineation Practices Handbook (1994), however, that edgelines as wide as 203.2 mm (8 in) be considered to provide the elderly driver with better preview distances.(2) However, this possibility was investigated by Hall (1987), who found no significant improvement in run-off-the-road accident occurrence; as a result, it was recommended that the use of these 203.2-mm (8-in) edgelines be discontinued.(20) Good and Baxter also investigated the use of wide edgelines and found that a width of 150 mm (5.9 in) was in fact beneficial to the driver; a combination of wide edgelines and Post-Mounted Delineators (PMDs) (or RPMs)—for short-range and long-range information, respectively—would be ideal.(18) Both lane line boundaries should therefore be delineated with RPMs supplementing the center line. According to Pennell, RPMs should not supplement right edgelines unless: (a) there is a fixed obstruction (e.g., guardrail, trees, poles, bridge rails, ditches) or there are difficult traveling surfaces exceptionally close to the edge of the roadway, or (b) there is a lane drop or road width reduction.(19)

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[1] Recommendations are presented in italics along with a justification where suggestions are extrapolated from research articles. Justifications are based on the findings of a literature search. Where there are unresolved issues, further research is proposed and discussed in a boxed section.

Future Research:

4. Guidelines should include specific information as to when and where left edgelines should be supplemented by RPMs, perhaps using lighting and ADT criteria.

5. Good and Baxter indicated that further studies with larger sample sizes should be conducted to confirm their results.(18) It is also imperative that the study include a sample of older drivers to ensure that the benefits of larger, more clear delineation to the older population is not discounted. Studies should also be conservative enough to include potential benefits of wide edgelines to drivers when faced with adverse weather conditions.

RPM LOCATION

The Roadway Delineation Practices Handbook needs to be more specific about where to and where not to use RPMs.[2] The traffic engineer should be able to assess whether RPMs are needed on the basis of variables such as ADT, street lighting, road geometry, and road structure. Some research suggests the use of RPMs under the following situations:

- *Supplement double-yellow centerlines with RPMs on two-lane rural curves.*
- *Delineate center and edgelines where there are pavement width reductions at a narrow bridge.*
- *Use RPMs at painted gores, exits, and bifurcations.*

Justification: Freedman et al. [3] reviewed several studies with respect to the effects of RPM delineation on lane position and speed, and found that the above practices produced positive results. For example, Niessner's study (1984) (cited in Freedman et al.) found that delineation of center and edgelines, where there are pavement width reductions at a narrow bridge, produced reductions in 85th percentile speeds and centerline encroachments. Niessner also reports that RPMs reduce erratic maneuvers when used at painted gores, exits, and bifurcations. Taylor et al. found that RPM delineation of gores, exits, and bifurcations provides advance warning and geometry definition of roadways, plus an added rumble effect if the vehicle strays.[13]

- *Install snowplowable RPMs on all freeways and interstate highways.*
- *Install snowplowable RPMs on State highways at locations determined by the Bureau of Traffic Engineering on the basis of accident data.*
- *Do not use snowplowable RPMs on interchange ramps.*

Justification: Pennell recommends the above practices.[19]

Future Research:

6. It would be useful to provide separate guidelines for those States that will invariably install snowplowable RPMs as opposed to non-snowplowable RPMs—especially since the cost-effectiveness may vary between States on the basis of weather conditions.

7. The cost-effectiveness/performance tradeoff should be investigated in order to determine whether RPMs should be used on road sections with broken lines. If RPMs are used to delineate a passing zone, they will be subjected to many impacts, reducing their life span when compared with other uses. However, a recent study by Zwahlen and Schnell (1996) suggested that longer preview distances would be beneficial where passing is allowed on both sides of the road (dashed line sections); their study showed that the driver had the worst and shortest preview conditions (2.14 s) when driving through these sections.[21] More information is required before making a recommendation.

RPM COLOR

The Roadway Delineation Practices Handbook outlines which color of RPM should be used on roadways and whether double or single RPMs are required. This information is presented in a set of 11 figures (figures 40 through 50) in chapter 7 of the handbook.[2] The following guidelines are included.

The Roadway Delineation Practices Handbook Standards:

- *Yellow markers should supplement yellow lines.*
- *White markers should supplement white lines.*
- *Red markers mean "wrong way".*
- *When two-way markers are used for entrance and exit areas, the red reflective side should face wrong-way motorists.*

Future Research:

8. Pennell recommended that guidelines for RPMs also include the following: clear markers should supplement white lines, and when two-way markers are used for motorist guidance, the nonreflective side should face wrong-way motorists as opposed to a red reflective side.[19] These factors contradict the current guidelines; further studies are needed to determine which approach is best.

9. Color coding with RPMs is not a current delineation practice, but it was suggested for use by earlier work in areas such as no-passing zones or merge/diverge areas. For example, a no-passing zone might be delineated with white markers at long spacing and yellow markers at short spacing, or by delineating a solid yellow line with markers as a warning where a solid white line is currently used (Taylor et al.).[13] Current standards outlined by the Roadway Delineation Practices Handbook only describe the use of colored RPMs to supplement the color of paint.[2] It might be useful to determine whether the color of RPMs might provide the driver with additional information.

RPM PLACEMENT

The Roadway Delineation Practices Handbook presents a set of 11 figures (figures 40 through 50) that outlines where on the road RPMs should be placed.[2] Several roadway geometries and situations are included; the delineation handbook figures should be consulted for exact placement requirements and for visual reference.

The Roadway Delineation Practices Handbook Standards:

- *Place RPMs in line with and in gap of skip lines.*
- *Place RPMs between double-yellow centerlines when used on two-way, two-lane roads.*
- *Place RPMs outside double-yellow centerlines, on both sides of traffic, when used on two-way, multilane roads.*
- *Offset RPMs 50.8-76.2 mm (2-3 in) from a solid edgeline, specifically to the traffic side of left edgelines.*
- *Offset RPMs to the traffic side of left edgelines on exit and entrance ramps.*
- *Retroreflective RPMs should be placed so that the face is perpendicular to a line parallel to the roadway centerline.*
- *RPMs should not be placed over longitudinal or transverse joints of the pavement surface.*
- *Offset RPMs 50.8-76.2 mm (2-3 in) from the edge of solid paint or thermoplastic markings to avoid painting.*

The Following Guidelines Should Also be Included:

- *Ensure that there is a 152.4-mm (6-in) space between double solid-yellow center lines instead of a 203.2-mm (8-in) space to prevent RPMs from being painted.*
- *Concrete joints should not be straddled by a snowplowable RPM (unless lane narrowing will occur because of the offset RPMs).*

Justification: Pennell suggested these two additional guidelines after reviewing several research studies.[19] The emphasis on snowplowable RPMs is useful to ensure that all States can be accommodated.

- *For typical "cloverleaf" entrance/exit ramps (i.e., 4.9-m (16-ft) wide, radius ~73.2 m (240 ft), therefore about 24-degree curve), place RPMs on the outer edge of the ramp.*
- *Turn each RPM so that the angle between the tangent of the outer edgeline and the reference axis of the RPM is 15 degrees.*

Justification: According to Zwahlen (1987), if a 0.31-0.61 m (1-2 ft) solid body of grass or snow exists on both sides of the curve, the view of the curve's inner edgeline may be limited. RPMs on the outer edge would provide the driver with a longer arc, which is exposed to a direct line of sight.[22] This would allow the driver to have a longer preview time of the curve and improved outline for easier perception. The angle of the RPM should be adjusted for curves as recommended in the second guideline above because when the front surface of the RPM is perpendicular to the driver's line of sight, which intersects the outer edgeline at 30.5 m (100 ft) in front of the car, the photometric performance of the RPM will be improved.[22]

- *If RPMs are used to delineate outside of the traffic lane, place at the location of the lane boundary.*

Justification: Results by Blaauw show this configuration to be best.[17]

Future Research:

10. The current standards need to be specific for all situations. Currently, the Roadway Delineation Practices Handbook indicates in figure 40 (page 88) that RPMs should be placed inside double-yellow centerlines when used on two-lane, two-way roads, yet figures 44, 45, 47, and 48 all show situations where RPMs are placed outside double-yellow centerlines when used on two-lane, two-way roads.[2] The Handbook needs to clarify which pattern should be used under which circumstances.

11. Although recommendations currently suggest that ramps are delineated with RPMs on the left side only, according to Taylor et al., the "pathway to be driven within" should be defined as opposed to the "line to stay next to." They suggested placing RPMs on both edges for ramps or diverging roadways.[13] According to Kahn (1979) (cited in Migletz et al.) the level of guidance for night driving is increased when RPMs are placed on the inside and outside of curves.[2] These possibilities require further investigation.

12. Those preparing final guidelines for the various regions should consult the recommended guidelines made in New Jersey by Pennell, which support the current standards for: placing RPMs in line with and gap of skip lines, to offset RPMs from a solid edgeline, to offset RPMs to the traffic side of left edgelines, and to place RPMs between double yellow centerlines.[19]

RPM SPACING IN TRAFFIC ZONES

The MUTCD states that broken lines are usually formed on the basis of a 3-1 segment-to-gap ratio, with a 12.2-m (40-ft) cycle length of N (gap + segment) where the gap is 9.2 m (30 ft) and the marking segment is 3.1 m (10 ft) in length.[1] Figures 40 through 50 in the Roadway Delineation Practices Handbook also assume these dimensions; theses figures should be consulted for exact placement requirements and for visual reference.[2]

The Roadway Delineation Practices Handbook Standards for Tangents and Horizontal Curves:

Centerline Patterns

- *Supplement double solid-yellow centerline on a two-lane, two-way road with RPMs spaced at 2N —24.4 m (80 ft)—placed between lines.*
- *Supplement centerline indicating passing in one direction, on a two-lane, two-way road with RPMs spaced at 2N—24.4 m (80 ft)—placed between skip lines.*
- *Supplement center skip lines indicating passing in both directions, on a two-lane, two-way road with RPMs spaced at 2N—24.4 m (80 ft)—placed between skip lines.*
- *Supplement centerlines indicating a transition from passing in both directions to no passing zone, on a two-lane, two-way road with RPMs spaced at 2N—24.4 m (80 ft)—placed between skip lines, and with RPMs spaced at N—12.2 m (40 ft)—placed outside of double solid-yellow lines.*
- *Supplement double solid yellow centerline on a multilane, two-way road with RPMs spaced at N—12.2 m (40 ft)—placed beside lines, specifically 50.8-76.2 mm (2-3 in) away.*

Laneline Patterns

- *Supplement broken lanelines with RPMs spaced at 2N—24.4 m (80 ft)—unless otherwise specified, placed between skip lines.*

Edgeline Patterns

- *Supplement solid left edgeline with RPMs spaced at N—12.2 m (40 ft)—placed to the inside of the lane, 50.8-76.2 mm (2-3 in) away from the line.*
- *Do not usually supplement solid right edgeline with RPMs.*

Specific Horizontal Curve Patterns

- *Use 2N—24.4 m (80 ft)—when the degree of curvature is less than 3 degrees.*
- *Use N—12.2 m (40 ft)—when the degree of curvature is greater than or equal to 3 degrees but less than 15 degrees.*
- *Use N/2 —6.1 m (20 ft)—when the degree of curvature is greater than or equal to 15 degrees.*
- *For curves greater than 20 degrees, use two RPMs.*

Justification: The borderline cases (when the degree of curvature is equal to 3 or 15 degrees) in the specific horizontal curve pattern guidelines have been moved to the next, more conservative level, as recommended by Pennell.[19] The maximum spacing for curves of 3 degrees or more is therefore 12.2 m (40 ft), and the maximum spacing for curves of 15 degrees or more is 6.1 m (20 ft).

The Following Guidelines Should Also be Included:

- *If right edgelines present an exceptional hazard as described below, supplement with RPMs spaced at 6.1 m (20 ft). Also supplement paint for a reasonable distance of treatment before hazard.*

Justification: Since current guidelines state that "RPMs usually do not supplement solid right edgelines," instructions for RPM use and spacing provided by Pennell for hazardous situations would appear to be an asset. RPMs should not supplement right edgelines unless: (a) there is a fixed obstruction (e.g., guardrail, trees, poles, bridge rails, ditches) or difficult traveling surfaces exceptionally close to the edge of the roadway or (b) there is a lane drop or road width reduction.[19]

- *If RPMs are used on center or lane boundaries, on straight tangents, the maximum spacing should be 24.4 m (80 ft).*
- *If RPMs are used on center or lane boundaries, on 200-m (656-ft) radius curves (this translates into curves with ~ 8-9 degrees of curvature), the maximum spacing should be 12.2 m (40 ft).*

Justification: Current guidelines do not provide an upper boundary for RPM spacing, simply a recommendation based on the cycle length of road markings. If the cycle length of 12.2 m (40 ft) is changed, it will impact RPM spacing criteria. Blaauw indicates that, for straight sections, RPM spacing distances up to 24 m (78.7 ft) required information less often.[17] The 36-m (118-ft) configuration was less favorable. Therefore, it was suggested that the RPM spacing distances be restricted to no greater than 24 m (which is 78.7 ft—a little less than the spacing suggested in the guideline above, but since segment-to-gap ratios in the United States are based on units of feet, the recommended maximum spacing is given as 80 ft) on straight tangents unless further research is done to provide a more suitable upper boundary. Blaauw also indicates that, for 200-m (655.7-ft) radius curves, spacing distances for RPMs must be restricted to 12 m (~40 ft); spacing distances of 24 m (78.7 ft) and 36 m (118 ft) were found to lead to speed reductions and lane excursions. In general, it was found that "total observation time increases and driving performance deteriorates when less delineation information is present per unit of road length".[17] Upper or lower boundaries should be made for other degrees of curvature when there is sufficient information.

Future Research:
13. The suggestion to use supplemental RPMs on right solid edgelines under hazardous conditions states that the edgeline should have a "reasonable distance of treatment before the hazard." This reasonable distance needs to be quantified, either through empirical research or by

Future Research Continued

analytical means.

14. The current guidelines specify that centerlines are supplemented to indicate a transition from passing in both directions to no passing zone, on a two-lane, two-way road, with RPMs spaced at 2N—24.4 m (80 ft). These are placed between skip lines, and RPMs spaced at N—12.2 m (40 ft)—are placed outside of double solid-yellow lines. However, the guidelines provided by Pennell specify that special treatments should not be used for situations of passing, no passing, or a combination of the two.[19] Although recommendations made by Pennell support certain spacing standards, conflicting recommendations may reflect the need for region-specific guidelines. States that use snowplowable RPMs may require different guidelines for certain circumstances.

15. In figures 41, 42, and 44 in the Roadway Delineation Practices Handbook, alternate examples are given for spacing RPMs with a separation of N instead of 2N.[2] The Handbook needs to be more specific as to when or where this alternate spacing should be used.

16. In figures 41, 42, and 43 in the Roadway Delineation Practices Handbook, examples are given for RPM use without supplementing the painted delineation.[2] The Handbook needs to be more specific as to when or where this alternate system should be used.

17. When referring to segment-to-gap ratios, the MUTCD also states that dimensions other than the 3-1 ratio "may be used as best suits traffic speeds and need for delineation."[1] Since the placement of RPMs is directly dependent on the segment-to-gap ratio, it is suggested that the following two sources be considered to determine if an upper or lower boundary can be specified.

    Two sources indicated the possibility that insufficient delineation may induce drivers to speed up in order to increase information flow rate. Allen et al. reported that contrast thresholds reduce under dynamic conditions and reach a maximum at a frequency region of 2.5 Hz.[5] Therefore, in order to receive information at an optimal frequency of 2.5 Hz, the current 12.2-m (40-ft) cycle length would require a driver's speed to be 109.5 km/h (68 mi/h). If the cycle length were reduced to 7.3 m (24 ft), the optimum speed would be 43.5 km/h (27 mi/h). The study found that, when driving with a 12.2-m (40-ft) cycle length, there was an increased driver time delay at slow speeds, which resulted in the driver's "desire" to speed up.[5] Good and Baxter also found that the addition of some, but insufficient, delineation seemed to result in excessive speeds.[18] It was suggested by Allen et al. that if cycle lengths were kept small, perhaps it would avoid inducing inappropriate high speeds under adverse visibility conditions.[5] Recommendations for using a higher segment-to-gap ratio (i.e., shorter cycle length) would change the current 1:3 ratio with a cycle length of 12.2 m (40 ft) (producing a 3.05-m (10-ft) length with a 9.2-m (30-ft) gap) to, for example, a 3:5 ratio with a cycle length of 7.3 m (24 ft) (producing a 2.7-m (9-ft) line length with a 4.6-m (15-ft) gap).

    According to these sources, if the ratio is lowered too much, RPMs would be spaced too far apart and would not provide sufficient information. Ultimately, the delineation guidelines need to set strict criteria so that they require little speculation.

The Roadway Delineation Practices Handbook Standards for Lane Exits and Gores:

- *Use supplementing laneline red-white RPMs spaced at N—12.2 m (40 ft)—at least 305 m (1000 ft) in advance of an exit ramp and changing to single white RPMs at the gore nose. Delineate with red-white RPMs spaced at N/4—3.05 m (10 ft)—on both sides starting at the painted nose of the gore area and changing to single yellow RPMs spaced at N—12.2 m (40 ft)—on the ramp at the gore nose. (see Figure 49a in the Roadway Delineation Practices Handbook)*
- *Use supplementing laneline red-white RPMs spaced at N—12.2 m (40 ft)— at least 305 m (1000 ft) before entrance ramp and changing to single white RPMs at the gore nose. Delineate entrance ramp with single yellow RPMs spaced at N—12.2 m (40 ft)—prior to the gore nose, whereupon the spacing changes to N/4—3.05 m (10 ft). The spacing returns to N—12.2 m (40 ft)—at the merging end. (see Figure 49b in the Roadway Delineation Practices Handbook)*

Future Research:

18. Pennell suggests that supplemental RPMs be spaced at 6.1 m (20 ft) for painted gores unless the gore exit is shorter than 24.4 m (80 ft), in which case, spacing should be 3.05 m (10 ft).(19) The Roadway Delineation Practices Handbook specifies a spacing of N/4—3.05 m (10 ft)—for the gore area of exit and entrance ramps.(2) This suggestion may have been made because snowplowable raised pavement markers (SRPMs) are used extensively in New Jersey. Consideration should be given as to whether this recommendation should also be implemented in other States where SRPMs are used.

19. Consider the progress of research concerning paint markings, for it might affect the current recommendation for RPMs (use and/or spacing). For instance, Fitzpatrick, Lance, and Lienau (1995) found that drivers moved into or out of the exiting lane further upstream of the lane drop gore after pavement markings were used at freeway lane drop exits. (23) The number of maneuvers also decreased; the largest decrease was in the number of one-lane changes through the gore. If the gore markings are supplemented with RPMs, as recommended in the subsection above, the areas with more frequent lane changes would suffer the greatest damage and loss of markers. Additional research should be done to address the best combination of paint and RPM location/spacing, as required for both day and night delineation.

20. Zwahlen considered the use of RPMs on cloverleaf entrance and exit ramps.(22) He suggested that four RPMs would be required in view to provide adequate preview time for the driver. The optimal spacing would therefore be 7.6 m (25 ft). He concluded that RPMs were not useful as delineation for cloverleaf entrance and exit ramps.(22) However, since he used a sample size of only 11 people, it is recommended that the experiment be redone with a larger sample size. Also, since RPMs were severed to achieve 50 percent of the initial reflectivity and left as long as 2 years, it is recommended that the experiment be redone with frequent measures of RPM reflectivity.

The Roadway Delineation Practices Handbook Standards for Narrow Bridges (on two-lane rural roads):

- *Use RPMs on both the center and edgeline spaced at 24.4 m (80 ft), decreasing to 12.2 m (40 ft) on approach to a narrow bridge to show the decrease in pavement width.*

The Roadway Delineation Practices Handbook Standards for Left-Turn Lanes:

- *For continuous center left-turn lane of three-lane road, space RPMs at distance N on the outside of the lane and 2N on the inside of the lane.*
- *For continuous center left-turn lane of five-lane road, space RPMs at distance N on the outside of the lane, 2N on the inside of the lane and, in addition, space RPMs at distance of 2N on the laneline.*

The Following Guidelines Should Also be Included:

- *For continuous center left-turn lanes, where RPMs are used between left-turn slots and through lanes, RPMs should be omitted for first 30.5 m (100 ft) to permit traffic to enter slots without crossing markers.*

Justification: Taylor et al. suggest this additional guideline.[13]

Future Research:
21. Pennell recommends that continuous center left-turn lanes should not be identified by specially spaced RPMs.[19] This suggestion may have been made because SRPMs are used extensively in New Jersey. Consideration should be given as to whether this recommendation should also be implemented in other States where SRPMs are used.

The Roadway Delineation Practices Handbook Standards for Intersections:

- *At a distance of 4N before the intersection of a two-lane, one-way road, change spacing of RPMs on centerline from N to N/2 .*
- *At a distance of 4N before the intersection of a two-lane, two-way road, change spacing of RPMs on centerline from N to N/2.*
- *At a distance of 4N before the intersection of a four-lane, two-way road, change spacing of RPMs on lanelines from N to N/2 (and place them in line with centerline RPMs).*

Future Research:

22. Pennell [19] recommends using the same spacing before intersections as is used for through movement; however, previous studies by Taylor et al. [13] and Bali, McGee, and Taylor (1976) [24] support the notion of reduced spacing before intersections. Pennell also made recommendations specific to signalized and unsignalized intersections, a distinction that may be useful for guidelines.[19]

23. One area of research considers the use of coded delineation to provide the driver with advance information about upcoming curves or intersections, but in such a way as to induce the driver to slow down. An initial review of the following research indicates that coded delineation may help the driver maneuver the vehicle both at intersections and through curves.

    The use of coded stripes as advance warning for curves was studied by Witt and Hoyos (1976) in a simulation experiment.[25] They found that with coded stripes: (a) the precision of course-following increased, especially in the approach zones to curves; (b) steering wheel turning became more steady and smooth; and (c) the drivers drove slower on difficult road sections and faster on easy road sections. Witt and Hoyos suggested follow-up field research in order for the results to be generalized to the real world.[25] After reviewing literature that investigated the potential benefits of transverse stripes as warnings before curves or at stop approaches, Bali et al. considered them to be effective at reducing the average speed and the variability around that average.[24] Bali et al. suggested the use of transverse stripes painted across approach lane(s) at gradually decreased spacing where a required stop is unexpected or in high accident areas. The use of thermoplastics was also suggested (as paint would wear away too fast), along with a bar width of 609.6 mm (24 in) and an overall pattern length of 152.5 m (500 ft).[24] Taylor et al. suggested that the principle of perceptual modification techniques might be applied to spacing of RPMs or PMDs. They thought that deliberate distortions of relative motion between marker and vehicle might produce the deceleration profiles required.[13] Blaauw also suggested relating the spacing of RPMs to road curvature like that used for stripes and PMDs.[17] In fact, a study by Zwahlen (1993) used an optical illusion in an attempt to reduce driver speeds.[26] He arranged PMDs to provide a perceptual illusion of increased curve sharpness by ascending (or descending) delineation heights. The height increments needed to be relatively large (e.g., 1.07 m (3.5 ft) to 1.65 m (5.41 ft) over a 72-m (236-ft) curve length); the results found a reduction in speed with significant center speed reduction from 49.69 km/h (30.88 mi/h) to 44.09 km/h (27.4 mi/h).[26] A study by Rockwell and Hungerford (1979) (cited in Zwahlen, 1993) also found a decrease in speeds through curves when a novel PMD system was used.[26] Further research is needed to determine whether the effect wears off over time.

    There are many coded delineation issues that remain unclear, such as what part of the curve (e.g., radius, degree of curvature) reveals the most essential elements of a turn (e.g., sharpness, width) and whether RPMs present this information early enough to warn the driver. The results of a study by Fildes and Triggs highlight a potentially dangerous illusion in the perception of curvature during the negotiation of bends in the road.[7] They found that, when drivers are asked to make judgments about curvature—similar to a situation commonly experienced as a driver moves along a curved two-lane highway—first, the driver will primarily make that judgment on the basis of the curve's deflection angle, and second, the radius of curvature is likely to be misinterpreted by drivers in their assessment. Subjects in the

Future Research Continued

experiment responded to small-radius, small-angled curves as least curved when in fact they were the mostcurved.[7] Thus, it seems important to ensure that the driver has as much information about the most important part of the curve as far ahead of time as possible. The curve-assessment process was shown by Cohen and Studach (1977), and McLean and Hoffman (1973) (cited in Fildes and Triggs) [7], and by Shinar et al. [4], to start well in advance of the vehicle entering the curve (at least 100 m (327.9 ft) before); far delineation is therefore essential to provide the necessary information.

The above research should be included in a thorough literature review, and further empirical studies should be conducted to answer questions such as: "Does the effect of coded delineation wear off over time?" and "How are accident rates affected by coded delineation?"

RPM SPACING IN CONSTRUCTION ZONES

The Roadway Delineation Practices Handbook provides guidelines as to how far apart to space Temporary Raised Pavement Markers (TRPMs) on the basis of road type and the length of time the road segment is under construction.[2] Some of these guidelines are outlined in the text, others in the figures in the Handbook.

The Roadway Delineation Practices Handbook Standards for Tangents and Horizontal Curves Outlined in the Text:

- *RPMs should supplement paint with a spacing of 12.2 m (40 ft) (a retroreflective RPM is placed midway between each 3.05-m (10-ft) paint stripe).*
- *If RPMs substitute for painted skip lines, a cluster of four nonretroreflective RPMs with a retroreflective RPM every 12.2 m (40 ft) or N is recommended. The non-retroreflective RPMs should be placed 1 m (3 1/3 ft) or N/12 apart to provide the daytime appearance of a skip line.*

The Roadway Delineation Practices Handbook Standards for Tangents and Horizontal Curves Outlined in the Figures:

- *RPMs should not be used on two-lane, two-way roads if work zones will last 3 days or less.*
- *RPMs should not be used on undivided or divided multilane roads with work zones.*
- *RPMs can be used to substitute paint on two-lane, two-way roads with severe curvature if work zones will last 14 days or less. A series of two RPMs are used, intra-spaced at N/20 and inter-spaced at 18N/20 (or N/2 distance from the first RPM in series 1 to the first RPM in series 2).*

The Following Guidelines Should Also be Included for Bridges With Grooved Decks, Relocated Exit Ramps, and Pavement Drop-Offs:

- *Provide transition area upstream and downstream of grooved bridge decks where temporary RPMs are used for delineation.*

Justification: Pennell made recommendations on the basis of an extensive literature review.[19] Since there are currently no guidelines that include this situation, it is suggested that this be included unless there is other research to show that it would not be advisable.

- *Use 2.1-m (7-ft) panels spaced 6.1 m (20 ft) apart with TRPMs spaced 3.05 m (10 ft) apart on the relocated exit ramp.*
- *Use drums spaced 24.4 m (80 ft) apart with TRPMs spaced 6.1 m (20 ft) apart on the mainline of a relocated exit ramp.*

- *When two lanes travel in the same direction and separate traffic, use supplementary temporary RPMs spaced 1.5 m (5 ft) apart for pavement drop-offs.*

Justification: Davis (1993) presented recommendations for RPM use after a literature search, a survey of professionals who made recommendations for improvement, a driver survey of photographic slides to determine which designs merited further study, and a driver video survey used to verify results.(27) Those listed above were among the final suggestions resulting from this study. They should be used in conjunction with Part VI of the MUTCD: Standards and Guides for Traffic Controls for Street and Highway Construction, Maintenance, Utility, and Incident Management Operations, 1993 revisions, (28) and the Roadway Delineation Practices Handbook.(2)

Future Research:

24. The Roadway Delineation Practices Handbook lists the following guidelines in the text and refers to figure 50 for clarification of RPM placement in work zones.(2)

RPMs should supplement paint with a spacing of 12.2 m (40 ft) (a retroreflective RPM is placed midway between each 3.05-m (10-ft) paint stripe).

If RPMs substitute painted for skip lines, a cluster of four nonretroreflective RPMs with a retroreflective RPM every 12.2 m (40 ft) or N is recommended. The nonretroreflective RPMs should be placed 1 m (3 1/3 ft) or N/12 apart to provide the daytime appearance of a skip line.

However, both RPM type and spacing are depicted differently in figure 50 than is written in the text. According to the figure, the following guidelines should be used:

RPMs can be used to substitute paint on two-lane, two-way roads if work zones will last 14 days or less. A series of three RPMs will be intra-spaced at N/12 and inter-spaced at 10N/12 (or N distance from the first RPM in series 1 to the first RPM in series 2).

RPMs can be used to substitute paint on two-lane, two-way roads if work zones will last over 14 days. A series of three RPMs will be intra-spaced at N/12 and inter-spaced at 10N/12 (or N distance from the first RPM in series 1 to the first RPM in series 2), and accompanied by painted edgelines.

RPMs can be used to substitute for paint on two-lane, two-way roads with severe curvature if work zones will last 14 days or less. A series of two RPMs are used, intra-spaced at N/20 and inter-spaced at 18N/20 (or N/2 distance from the first RPM in series 1 to the first RPM in series 2).

This discrepancy needs clarification. It is also important that the guidelines specify under which circumstances paint should be replaced by RPMs rather than be supplemented by them.

25. Pennell recommended that TRPMs should be spaced at 1.5 m (5 ft) or N/8 with retroreflective units at 6.1 m (20 ft) when substituting stripes.(19) This should be considered when

Future Research Continued

determining which source (text or figures) reflects the guidelines of the Roadway Delineation Practices Handbook.

26. The results of the study by Davis were used to make recommendation for the preferred way to delineate at curves, drop-offs, and relocated ramps. (27) The final recommendations for RPMs were listed in the subsection above; there were also a series of suggested study areas that emerged from the survey of professionals who had delineation experience. Some of these were not included in the final experiments, and may warrant further research. For horizontal and vertical curves, consider supplemental retroreflective RPMs spaced 6.1 m (20 ft) apart or retroreflective RPMs spaced 1.8-3.05 m (6-10 ft) apart when used without paint. For relocated entrance ramps, consider supplemental RPMs spaced at 3.05 m (10 ft) and RPMs spaced at 1.5 m (5 ft) when used without paint.

RPM TYPE

A description of the features that should be incorporated for nonretroreflective RPMs, retroreflective RPMs, snowplowable RPMs and temporary (construction zone) RPMs should be included in the guidelines to provide a buyer's guide for RPMs. It would also be useful if the guidelines included a list of currently available RPMs that meet those requirements. The Roadway Delineation Practices Handbook provides such features for construction zone RPMs, but is lacking for the other two RPM types.(2) Some suggested features are listed below along with a list of RPM models that may fulfill future requirements.

The Following Features Should be Incorporated for Nonreflective RPMs:

- *Ceramic RPMs should have a textured bottom surface that adheres to the following specifications:*
  - *(i) free from gloss or glaze*
  - *(ii) have a number of integrally formed protrusions of 1.27 mm (0.05 in)*
  - *(iii) protrusions project from the surface in a uniform pattern of parallel rows*
  - *(iv) protrusions shall have a flat surface parallel to the bottom of the marker with an area between 65.2 and 41.9 mm² (0.101 and 0.065 in²)*
  - *(v) combined area of faces between 1419 and 2581 mm² (2.2 and 4 in²)*
  - *(vi) protrusion shall be circular in section*
  - *(vii) number of protrusions should not be less than 50 or more than 200*
  - *(viii) sides of protrusion may be tapered (to facilitate forming and mold release)*
  - *(ix) must not exceed radius of 15 degrees from perpendicular to marker bottom*
  - *(x) markers manufactured with protrusions having diameter less than 0.38 cm (0.15 in) may have additional taper not exceeding 30 degrees from perpendicular to marker bottom and extending no more than one-half the total height of the protrusion*
- *Overall height of marker should be between 1.72 and 2.03 cm (0.68 and 0.80 in).*

Justification: These are the specifications used by the California Department of Transportation (Caltrans), as cited in the Roadway Delineation Practices Handbook, for nonreflective ceramic markers.(2) This should be considered when compiling national guidelines for nonreflective RPMs.

The Following Features Should be Incorporated for Retroreflective RPMs:

- *A corner-cube reflector lens.*
- *Acrylic based.*
- *A plastic mounting.*
- *Projection of 1.8 mm (0.073 in) above the roadway.*

Justification: There are several different types of retroreflective RPMs listed in the Roadway Delineation Practices Handbook. Blaauw and Padmos found that the corner-cube reflector with plastic mounting provided the driver with the greatest visibility distance (extrapolated for clear, dry, wet, and fog conditions) when compared with paint, thermoplastics, profile tape, and biconvex lens RPMs.(6) Additional research is required to give final specifications of each feature (see the future research issues discussed at the end of this subsection).

The Following Features Should be Incorporated for Snowplowable RPMs:

- *Casting with a 6-degree slope.*
- *Cast-iron housing measuring 235 by 149 by 44 mm (9 1/4 by 5 7/8 by 1 3/4 in).*
- *Maximum projection of 10 mm (7/16 in) above the roadway.*
- *Acrylic prismatic retroreflector with a 1104.5 mm^2 (62 in^2) surface per face.*

Justification: The Roadway Delineation Practices Handbook lists the above features when describing snowplowable RPMs.(2) Some of the above features may be specific to one model; more general information could be specified for incorporation into the guidelines.

The Following Features Should be Incorporated for Construction Zone RPMs:

- *A streamlined profile.*
- *A microscopic, cube-corner, sealed prismatic air cell, cube-corner reflex, or multiple glass lens reflector.*
- *The area exposed to the driver's normal line of vision balanced between the casing itself and the retroreflective insert.*

Justification: The Roadway Delineation Practices Handbook lists the above features for incorporation into the design of construction zone RPMs.(2)

RPM Types Expected to Fulfill Future Requirements:

The following list of RPM types is only a sample and does not address cost-effectiveness, although the final version should consider such a variable when compiling a list of available RPMs.

- *Stimsonite models 911, 948, or 953 Retroreflective Raised Pavement Markers (RRPMs) once AADT reaches 10 000 vpd/lane. These acrylic based corner-cube lens reflectors have an additional glass layer to protect the reflector from damage and had the lowest combination of percent of RPMs damaged or missing.*
- *Stimsonite 96 LP Snowplowable RPM is suggested for use.*
- *Refer to study listed below for the temporary RRPMs best used for adequate day and night delineation in construction and work zones.*

Justification: Several models of corner-cube reflectors, a microprism high-intensity sheeting reflector, and a Swareflex reflector with 1/3 cm (1/8 in) glass beads were evaluated by Ullman (1994).(29) Factors such as volume of vehicle exposure, degradation in reflectivity, damage, and missing percentages were all included. Results concluded that moderately performing RRPMs (Apex 921, Apex 918, Apex 928, Batterson Reflective Button, Ray-O-Lite 8704(S), Ray-O-Lite

8704(R), Stimsonite 88) performed reasonably well under lower volume exposure (Site 4), but when exposed to higher volume conditions (Site 1), their reflectivity degraded below the SI value of 0.5 by about 7 months. High-performance RRPMs (Ray-O-Lite 9704, Ray-O-Lite 2002, Ray-O-Lite 2003, Stimsonite 911, Stimsonite 948, Stimsonite 953, Swareflex) provided at least minimum reflectivity at most sites for an entire year or more. Several still provided fairly high levels of reflectivity at low-volume sites after 2 years, but at the highest volume site, only Stimsonite models maintained minimum reflectivity up to and beyond 1 year. Of the high-performance models, the Stimsonite 911, 948, and 953 had the lowest percent of damage and number of missing markers (14.8 percent and 0 percent, 14.8 percent and 10 percent and 14.8 percent and 3.6 percent, respectively).[29]

A literature review conducted by Pennell found two sources that indicate that the Stimsonite 96 LP was the most durable snowplowable RPM. This marker was the best of four types tested in a study done in California by Lougheed (1986), and was also found to be the best of three markers tested in a study by Bryden and Lorini (1981) (cited in Pennell).[19]

A study by Khan (1987) (cited in the Roadway Delineation Practices Handbook) proved that only one TRPM provides adequate day and night delineation for construction and work zones.[2] This study by Khan must be consulted directly to obtain the name of the TRPM; it was unavailable when the current report was prepared.

Future Research:

27. More information is required in order to compile a final list of features that should be incorporated for RPM types. A minimum reflectivity criteria for RPM effectiveness has yet to be established and will influence the level of reflectivity required for new RPMs. Cost analyses will determine whether a minimum half-life is required. Research to determine lens types, damage protectors, mountings and other special features will most likely follow production-driven studies. Documentation of acceptable features should be extrapolated from these sources.

RPM APPLICATION AND MAINTENANCE

Assuming that a step-by-step user manual accompanies RPMs when they are purchased, the following recommendations will focus on research-based issues. Just as when determining which type of RPM to use, the determination of application materials and installation procedures and maintenance will also most likely be product-driven. Ideally, the ability to match road type, RPM type, and bonding material will allow the most cost-effective combinations to be applied. The Roadway Delineation Practices Handbook outlines several limitations that should be considered when determining which combination of marker and bonding to use for certain road types.[(2)] However, more details are needed to create a national guide for installation, application materials, and maintenance of RPMs. The following information should be used to set guidelines to indicate which procedures and which materials should be used for particular circumstances (based on region, weather, road type, ADT, etc.)

Some Facts About RPM Installation:

- *RPMs should not be set if relative humidity is more than 80 percent or if pavement surface is not dry.*
- *Installation of RPMs should not be made for 1 year after the application of a rejuvenating agent on asphalt pavements.*

<u>Justification:</u> The above installation limitations are mentioned in the Roadway Delineation Practices Handbook.[(2)] Other limitations outlined by the manufacturer should also be included in final guidelines.

Some Facts About Application Materials:

- *The bonding capability of butyl pads (used for self-adhesive RPMs) is reduced when temperatures are below 10 °C (50 °F).*
- *Some standard set epoxy adhesives require temperatures (air and pavement) above 10 °C (50 °F).*
- *Rapid-set epoxy formulas are usually applied in temperatures as low as -1 °C (30 °F).*
- *Use bitumus adhesive to apply RPMs to new (softer) asphalt surfaces.*
- *Use well mixed (uniformly gray) epoxy adhesive or bitumus adhesive to apply RPMs to older pavement surfaces and for pavements with a high volume of traffic.*

<u>Justification:</u> The above facts are stated in the Roadway Delineation Practices Handbook, in Tielking and Noel (1989),[(30)] and in McNees (1987).[(31)]

Some Facts About the Maintenance of RPMs:

- *The Retro-Skip device, developed by Caltrans to skip RPMs when painting, has been successfully tested at speeds up to 105 km/h (65 mi/h) with ~99 percent accuracy.*

- *The Retro-Skip device works well on Portland cement concrete or asphalt concrete pavement and is easily installed on any marking equipment with gun control.*
- *An experimental washing device for RPMs (developed by Caltran) may be useful to remove rubber residue from RPMs.*
- *Modified snowplows with a plastic shovel (as opposed to a steel shovel) should prevent snowplowable RPMs from being damaged.*
- *Construction adhesive used to replace reflectors in casting of snowplowable RPMs was found most durable.*
- *Replacing a missing marker with a new marker directly on the failure spot instead of alongside was found to be durable.*

Justification: The above information was taken from various sources. The first three points are outlined by the Roadway Delineation Practices Handbook.(2) Pennell gives snowplow and replacement recommendations in guidelines for highway delineation.(19) Tielking and Noel report that on a test section of road, markers that were replaced with epoxy, alternately in front of and on top of the failure spots in the skip stripe gaps, were found to all be in place 22 months later. The method used included using a shot of compressed air to blow debris out of the failure depression before filling it with epoxy and placing a marker on top.(30)

Future Research:

28. Zwahlen explains the use of OCARD (ODOT Computer Aided Road Delineation)—a knowledge-based system that computes the delineation layout using consistent and uniform delineation—in his study "Optimal Application and Placement of Roadside Reflective Devices for Curves on Two-Lane Rural Highways."(26) If it is possible to adapt this software system for the use of RPMs, it may aid the traffic engineer in the application of RPMs and make the task more efficient. The potential of this package should be investigated further.

29. As of yet, there are no national guidelines for when to replace an RPM. Since the criteria for determining minimum acceptable reflectivity for RPMs are not yet resolved, further research must be done in order to set a criterion in place. Currently, individual States determine which criteria to use for replacement procedures, based not on minimum reflectivity but on missing markers. Freedman et al. indicate several States that use different criteria to determine "effectiveness" of RPMs and therefore when to replace them: (3)

California	RPMs are replaced when two or more consecutive markers are missing.
Florida	RPMs are replaced when eight or more consecutive markers are missing.
Texas	RPMs are replaced when 50 percent or more markers are missing within 1.6 km (1 mile) of highway.
Massachusetts	Replaces only reflective lens if casting is intact.
Michigan	Replaces only reflective lens if casting is intact.
New Jersey	Replaces only reflective lens if casting is intact.
Massachusetts	Snowplowable RPMs are replaced when 30 percent or more markers are missing.
New Jersey	Uses visual inspection.

Future Research Continued

Future Research Concluded

Pennsylvania RPMs are replaced as needed, determined by visual inspection.

Since the effectiveness of RPM delineation requires both adequate reflectivity and adequate numbers, it would be ideal to determine a replacement criterion based on both factors. The Delineation Practices Handbook refers to a study by McNees (1987), which sought to determine a procedure that could be used to evaluate the effectiveness of RPM and raised traffic button systems.(31) The evaluating criteria include both reflectivity and loss of markers as indicators of replacement. However, the proposed procedure still requires further investigation. The experimental procedure and, thus, in turn, the proposed evaluation procedure does not account for additional variability.(31) Further research could determine whether evaluations might be biased by factors such as film processing, comparing scenes taken from different cameras or film sets, or whether color film produces significantly different representations from black and white film. Other factors that might bias the contrast or brightness of the photograph should also be investigated, so that a precise procedure might be provided. Lee, Hostetter, and Leibowitz (1991) include some information about controlling for contrast that is useful.(32)

If the method of evaluating photographs proves insufficient, it is still necessary to apply a criterion to determine whether RPMs should be replaced. One issue to consider however, is how one accurately applies such a criterion to RPMs in the field while they are attached to the road. One study addresses some of the problems in measuring wet night performance and discusses the mobile laser retroreflectometer. This measuring device is described as being able to measure background luminance and it records both the coefficient and the contrast luminance of a line along significant distances of road (DeJaiffe, 1987).(33) The progress of this research should be monitored, along with the possibility of measuring RPMs with a mobile device with similar capabilities.

One alternative to measuring reflectivity in the field is to find a relationship between field and laboratory measurements such that laboratory-controlled studies can accurately reflect what would be found in the field. A study by King and Graham (1989) found that there is a strong relationship between test subject subjective evaluation of field luminance and laboratory evaluation of luminance. (34) This relationship can be expressed mathematically and the resulting equation used to calculate "field factors" relating laboratory-produced evaluations to actual field evaluations. If King and Graham's findings can be verified, future research could then be conducted in the laboratory under controlled and safe conditions with minimum field verification. The possibility of applying this method to RPM research should be considered.

RPM REFLECTIVITY

As mentioned previously, there is no current standard for minimum RPM reflectivity on the basis of how much information the driver requires for controlled driving performance. However, several sources provide information that might be useful in determining this criterion. To determine how bright RPMs need to be relative to their surroundings to provide adequate delineation, several issues must first be established. Establishing a minimum preview distance for the average driver must account for the increased processing time and decreased discrimination ability of the older driver. Establishing which level of contrast will optimize driver performance must account for ambient lighting, weather conditions, headlight glare, and the complexity of the surroundings. The Roadway Delineation Practices Handbook discusses these issues and establishes the criterion of 100 millicandelas per lux per square meter as the minimum value for coefficient of retroreflected luminance, R_L, for pavement markings on dry roads.(2) The same type of criterion is needed for RPMs, measured with the coefficient of retroreflection R_A (as used for traffic signs). It is explicitly stated in the Roadway Delineation Practices Handbook that the two coefficients should not be compared as they are measured differently, but there are a few facts mentioned that should be considered when developing a criterion for RPM markings.(2)

Facts About Driver Visibility Requirements Made by the Roadway Delineation Practices Handbook:

- *Drivers 65 and older may require four times as much light to see as well as a 39-year-old.*
- *Older drivers adopt less flexible searching strategies.*
- *Driver perception-reaction time continually increases with age.*
- *Recommendations were made to double the value of luminance contrast to account for older or impaired drivers.*
- *Two s of preview time is required for short-range guidance and a minimum of 3 s is required for long-range guidance. At 40 km/h (25 mi/h), delineation must be visible at least 34 m (110 ft) ahead; at 90 km/h (55 mi/h), delineation must be seen at least 76 m (250 ft) ahead.*
- *Optimal contrast levels and, therefore, the required reflectivity of RPMs to allow for processing at a higher level must account for conditions (such as fog, rain, dew, glare) that could alter a minimum contrast achieved in clear, dry weather.*

Facts About Driver Visibility Requirements Made by Other Sources:

- *There is evidence that after 11 months RPMs with a mean SI level of 0.1 retained operational effectiveness with respect to near delineation but that their effectiveness as a far delineator was degraded (Krammes and Tyer).(14)*
- *New corner-cube RPMs in clear weather had a threshold visibility distance of 243 m (790 ft) when dry and 198 m (660 ft) when wet. New corner-cube RPMs in fog had a threshold visibility distance of 109.8 m (360 ft) when dry and 100.6 m (330 ft) when wet (Blaauw and Padmos).(6)*
- *Worn (by 2 M vehicles) corner-cube RPMs in clear weather had a threshold visibility distance of 131.5 m (430 ft) when dry and 140.3 m (460 ft) when wet. Worn corner-cube*

RPMs in fog had a threshold visibility distance of 70.2 m (230 ft) when dry and 109.8 m (60 ft) when wet (Blaauw and Padmos).[6]

Future Research:

30. Given how the luminosity requirements for delineation are outlined (based on research performed by Freedman et al. [3]) in the Roadway Delineation Practices Handbook [2], if possible, the same basic method should be applied to determine minimum contrast levels for RPMs. If a minimum reflectivity criteria cannot be achieved through this method, information from the study by Blaauw and Padmos should be expanded to determine a criterion on the basis of visibility distances.[6]

31. If contrast can be used to determine a minimum reflectivity criterion, the results of the computerized headlight evaluation model (DETECT) used by Freedman et al. may be useful.[3] They showed that, for centerline visibility, if a single vehicle providing glare is between 100 and 300 m (327.9-983.7 ft) away, the contrast on dry pavement needs to be eight times greater than when there is no glare source in order to preserve a 3-s preview time. On wet tangents, for a single oncoming vehicle at 300 m (983.7 ft) away, the contrast needs to be four to eight times greater than the contrast needed when there is no glare source to preserve 2 s of preview time.[3]

32. Given that Blaauw and Padmos used a required preview time of 5 s, in clear weather the required preview distance for delineation would have had to be 110 m (360.6 ft) when the velocity was 80 km/h (49.7 mi/h) and 140 m (459 ft) when the velocity was 100 km/h (62.1 mi/h).[6] In fog, the required preview distance for delineation would have had to be 100 m (327.9 ft) when the velocity was 70 km/h (43.5 mi/h) and 110 m (360.6 ft) when the velocity was 80 km/h (49.7 mi/h). According to these findings, at a speed of 80 km/h (49.7 mi/h), the driver would have to be able to see delineation at least 110 m (360.6 ft) ahead in clear weather.[6] If these levels were adjusted using a preview time of 4 s (the upper limit for visibility distance to account for older or impaired drivers) and other conditions were taken into account (e.g., glare), it would be a starting point for determining a minimum reflectivity level based on visibility distance as opposed to contrast level.

SECTION 3. LOOK-UP TABLES

A working set of user-friendly guidelines is essential for the traffic engineer to have clear, concise instruction for RPM use. To provide the traffic engineer with the most efficient tool to make decisions regarding roadway delineation, it is suggested that a form of look-up table be developed to present the information in a clear and concise format. Ideally, this could be presented in a software package; the cells of a first-level table would have a hypertext link to an anchored second-level table. This would allow the user to point and click on the cell that requires more detailed information about delineation.

Each level should specify the use of RPMs on the basis of the evaluation of several variables. For instance, in order to determine if and how to delineate horizontal curves with RPMs, variables such as ADT, degree of curvature, super elevation, radius of curvature, and length of curve need to be specified. If it is determined that the road segment of interest qualifies for RPM delineation, a second-level table will provide the specifications of placement and spacing of markers according to passing/no-passing zones, lane width, ambient lighting, etc. The following is a rough example of a first- and second-level look-up table for tangent sections of road. If the characteristics of the road to be delineated match the criteria set for a two-way, two-lane rural highway in table 1, the user can then refer to the table listed in that cell (table 2) to obtain more detailed information about how and where to use RPMs.

Table 1. Example of a first-level look-up table to determine when delineation by RPMs is required for tangent road sections.

	By Average Daily Traffic (ADT)			
	Rural Highway (two-way)	**Divided Highway**	**Urban Street (two-way)**	**Urban Street (one-way)**
One-lane				
Two-lane	see table 2			
Multilane				
Not Specified				

Table 2. Example of a second-level look-up table to determine how to delineate using RPMs for a multilane tangent section of rural highway (two-way).

		Passing	No Passing
Double-Yellow Centerline Stripes	**Where**		
	Spacing		
Single White Laneline Stripes	**Where**		
	Spacing		
Solid Left Edgeline Stripe	**Where**		
	Spacing		
Solid Right Edgeline Stripe	**Where**		
	Spacing		

The variables used to determine RPM use are number of lanes, type of roadway, and ADT. Once it is determined that RPMs will be used, the engineer can look up placement and spacing information on the basis of striping and traffic zones. Matthias lists the practices of each State with regard to RPM use.(11) Although limited, the information provided by the State of Illinois can be used to demonstrate these look-up tables (refer to table 3). Boxes remain empty if no information is provided, and the "Not Specified" option is presented only to accommodate the information available by this source. Ideally, all boxes would have specific criteria for RPM use, or a statement such as "Do not delineate using RPMs" should be present. If one determined that the average daily traffic of a two-lane rural highway was greater than 15,000, the table would indicate that RPMs should be used to delineate the road. The user would then refer to the listed table (table 4) to determine the placement and spacing to be used.

Table 3. Example of a first-level look-up table to determine when delineation by RPMs is required for a tangent road section, using practices of Illinois.[11]

	By Average Daily Traffic (ADT)			
	Rural Highway (two-way)	Divided Highway	Urban Street (two-way)	Urban Street (one-way)
One-lane				
Two-lane	ADT ≥ 15,000 (see Table 4)			
Multilane		ADT ≥ 2500		
Not Specified				ADT ≥ 7500

Table 4. Example of a second-level look-up table to determine how to delineate using RPMs for a two-way, multilane tangent section of rural highway, using practices of Illinois.[11]

TABLE 4		Passing	No Passing
Double-Yellow Centerline Stripes	Where		
	Spacing		
Single White Laneline Stripes	Where	(IL) Not Specified	(IL) Not Specified
	Spacing	(IL) 80 ft c/c	(IL) 80 ft c/c
Solid Left Edgeline Stripe	Where		
	Spacing		
Solid Right Edgeline Stripe	Where		
	Spacing		

There is currently no national (or even regional) standard from which these tables can be generated. States may use vastly different criteria. For instance, according to Matthias, Illinois will use RPMs on two-lane, two-way rural highways if the ADT is greater than or equal to 15,000 vehicles/day. Wisconsin, however, will use RPMs to delineate two-lane, two-way rural highways if the ADT is greater than 6,000 vehicles/day.[11] It would be useful to standardize RPM use across the country (or within regions, to accommodate weather differences) for both when and how they are used.

SECTION 4. LIST OF FUTURE RESEARCH ISSUES

1. Future accident analyses should consider how variables such as road geometry, average daily traffic (ADT), and geographical region will affect the interpretation of results. Previous studies that have averaged over such variables should be re-evaluated.

2. Measurement of driving performance, including analyses of potential accidents because of curve lengthening when RPMs are used, should be investigated further.

3. Studies should report the driving situation that was investigated in terms specific to those set by FHWA guidelines. For example, if spacing specifications are described on the basis of the degree of curvature for horizontal curves, studies should report the road geometry in terms of degree of curvature. The reflectivity of RPMs should be measured in SI units and reported with reference to the minimum reflectivity criteria (yet to be established). These criteria along with required visibility distance should be used to evaluate RPM performance.

4. Guidelines should include specific information as to when and where left edgelines should be supplemented by RPMs, perhaps using lighting and ADT criteria.

5. Good and Baxter indicated that further studies with larger sample sizes should be conducted to confirm their results.(18) It is also imperative that the study include a sample of older drivers to ensure that the benefits of larger, more clear delineation to the older population is not discounted. Studies should also be conservative enough to include potential benefits of wide edgelines to drivers when faced with adverse weather conditions.

6. It would be useful to provide separate guidelines for those States that will invariably install snowplowable RPMs as opposed to non-snowplowable RPMs—especially since the cost-effectiveness may vary between States on the basis of weather conditions.

7. The cost-effectiveness/performance tradeoff should be investigated in order to determine whether RPMs should be used on road sections with broken lines. If RPMs are used to delineate a passing zone, they will be subjected to many impacts, reducing their life span when compared with other uses. However, a recent study by Zwahlen and Schnell (1996) suggested that longer preview distances would be beneficial where passing is allowed on both sides of the road (dashed line sections); their study showed that the driver had the worst and shortest preview conditions (2.14 s) when driving through these sections.(21) More information is required before making a recommendation.

8. Pennell recommended that guidelines for RPMs also include the following: clear markers should supplement white lines, and when two-way markers are used for motorist guidance, the nonreflective side should face wrong-way motorists as opposed to a red reflective side.(19) These factors contradict the current guidelines; further studies are needed to determine which approach is best.

9. Color coding with RPMs is not a current delineation practice, but it was suggested for use by earlier work in areas such as no-passing zones or merge/diverge areas. For example, a no-passing zone might be delineated with white markers at long spacing and yellow markers at short spacing, or by delineating a solid yellow line with markers as a warning where a solid white line is currently used (Taylor et al.).(13) Current standards outlined by the Roadway

Future Research Continued

Delineation Practices Handbook only describe the use of colored RPMs to supplement the color of paint.[2] It might be useful to determine whether the color of RPMs might provide the driver with additional information.

10. The current standards need to be specific for all situations. Currently, the Roadway Delineation Practices Handbook indicates in figure 40 (page 88) that RPMs should be placed inside double-yellow centerlines when used on two-lane, two-way roads, yet figures 44, 45, 47, and 48 all show situations where RPMs are placed outside double-yellow centerlines when used on two-lane, two-way roads.[2] The Handbook needs to clarify which pattern should be used under which circumstances.

11. Although recommendations currently suggest that ramps are delineated with RPMs on the left side only, according to Taylor et al., the "pathway to be driven within" should be defined as opposed to the "line to stay next to." They suggested placing RPMs on both edges for ramps or diverging roadways.[13] According to Kahn (1979) (cited in Migletz et al.) the level of guidance for night driving is increased when RPMs are placed on the inside and outside of curves.[2] These possibilities require further investigation.

12. Those preparing final guidelines for the various regions should consult the recommended guidelines made in New Jersey by Pennell, which support the current standards for: placing RPMs in line with and gap of skip lines, to offset RPMs from a solid edgeline, to offset RPMs to the traffic side of left edgelines, and to place RPMs between double yellow centerlines.[19]

13. The suggestion to use supplemental RPMs on right solid edgelines under hazardous conditions states that the edgeline should have a "reasonable distance of treatment before the hazard." This reasonable distance needs to be quantified, either through empirical research or by analytical means.

14. The current guidelines specify that centerlines are supplemented to indicate a transition from passing in both directions to no passing zone, on a two-lane, two-way road, with RPMs spaced at 2N—24.4 m (80 ft). These are placed between skip lines, and RPMs spaced at N—12.2 m (40 ft)—are placed outside of double solid-yellow lines. However, the guidelines provided by Pennell specify that special treatments should not be used for situations of passing, no passing, or a combination of the two.[19] Although recommendations made by Pennell support certain spacing standards, conflicting recommendations may reflect the need for region-specific guidelines. States that use snowplowable RPMs may require different guidelines for certain circumstances.

15. In figures 41, 42, and 44 in the Roadway Delineation Practices Handbook, alternate examples are given for spacing RPMs with a separation of N instead of 2N.[2] The Handbook needs to be more specific as to when or where this alternate spacing should be used.

16. In figures 41, 42, and 43 in the Roadway Delineation Practices Handbook, examples are given for RPM use without supplementing the painted delineation.[2] The Handbook needs to be more specific as to when or where this alternate system should be used.

17. When referring to segment-to-gap ratios, the MUTCD also states that dimensions other than the

Future Research Continued

3-1 ratio "may be used as best suits traffic speeds and need for delineation."[1] Since the placement of RPMs is directly dependent on the segment-to-gap ratio, it is suggested that the following two sources be considered to determine if an upper or lower boundary can be specified.

Two sources indicated the possibility that insufficient delineation may induce drivers to speed up in order to increase information flow rate. Allen et al. reported that contrast thresholds reduce under dynamic conditions and reach a maximum at a frequency region of 2.5 Hz.[5] Therefore, in order to receive information at an optimal frequency of 2.5 Hz, the current 12.2-m (40-ft) cycle length would require a driver's speed to be 109.5 km/h (68 mi/h). If the cycle length were reduced to 7.3 m (24 ft), the optimum speed would be 43.5 km/h (27 mi/h). The study found that, when driving with a 12.2-m (40-ft) cycle length, there was an increased driver time delay at slow speeds, which resulted in the driver's "desire" to speed up.[5] Good and Baxter also found that the addition of some, but insufficient, delineation seemed to result in excessive speeds.[18] It was suggested by Allen et al. that if cycle lengths were kept small, perhaps it would avoid inducing inappropriate high speeds under adverse visibility conditions.[5] Recommendations for using a higher segment-to-gap ratio (i.e., shorter cycle length) would change the current 1:3 ratio with a cycle length of 12.2 m (40 ft) (producing a 3.05-m (10-ft) length with a 9.2-m (30-ft) gap) to, for example, a 3:5 ratio with a cycle length of 7.3 m (24 ft) (producing a 2.7-m (9-ft) line length with a 4.6-m (15-ft) gap).

According to these sources, if the ratio is lowered too much, RPMs would be spaced too far apart and would not provide sufficient information. Ultimately, the delineation guidelines need to set strict criteria so that they require little speculation.

18. Pennell suggests that supplemental RPMs be spaced at 6.1 m (20 ft) for painted gores unless the gore exit is shorter than 24.4 m (80 ft), in which case, spacing should be 3.05 m (10 ft).[19] The Roadway Delineation Practices Handbook specifies a spacing of N/4—3.05 m (10 ft)—for the gore area of exit and entrance ramps.[2] This suggestion may have been made because snowplowable raised pavement markers (SRPMs) are used extensively in New Jersey. Consideration should be given as to whether this recommendation should also be implemented in other States where SRPMs are used.

19. Consider the progress of research concerning paint markings, for it might affect the current recommendation for RPMs (use and/or spacing). For instance, Fitzpatrick, Lance, and Lienau (1995) found that drivers moved into or out of the exiting lane further upstream of the lane drop gore after pavement markings were used at freeway lane drop exits.[23] The number of maneuvers also decreased; the largest decrease was in the number of one-lane changes through the gore. If the gore markings are supplemented with RPMs, as recommended in the subsection above, the areas with more frequent lane changes would suffer the greatest damage and loss of markers. Additional research should be done to address the best combination of paint and RPM location/spacing, as required for both day and night delineation.

20. Zwahlen considered the use of RPMs on cloverleaf entrance and exit ramps.[22] He suggested that four RPMs would be required in view to provide adequate preview time for the driver. The optimal spacing would therefore be 7.6 m (25 ft). He concluded that RPMs were not useful as delineation for cloverleaf entrance and exit ramps.[22] However, since he used a

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sample size of only 11 people, it is recommended that the experiment be redone with a larger sample size. Also, since RPMs were severed to achieve 50 percent of the initial reflectivity and left as long as 2 years, it is recommended that the experiment be redone with frequent measures of RPM reflectivity.

21. Pennell recommends that continuous center left-turn lanes should not be identified by specially spaced RPMs.(19) This suggestion may have been made because SRPMs are used extensively in New Jersey. Consideration should be given as to whether this recommendation should also be implemented in other States where SRPMs are used.

22. Pennell (19) recommends using the same spacing before intersections as is used for through movement; however, previous studies by Taylor et al. (13) and Bali, McGee, and Taylor (1976) (24) support the notion of reduced spacing before intersections. Pennell also made recommendations specific to signalized and unsignalized intersections, a distinction that may be useful for guidelines.(19)

23. One area of research considers the use of coded delineation to provide the driver with advance information about upcoming curves or intersections, but in such a way as to induce the driver to slow down. An initial review of the following research indicates that coded delineation may help the driver maneuver the vehicle both at intersections and through curves.

    The use of coded stripes as advance warning for curves was studied by Witt and Hoyos (1976) in a simulation experiment.(25) They found that with coded stripes: (a) the precision of course-following increased, especially in the approach zones to curves; (b) steering wheel turning became more steady and smooth; and (c) the drivers drove slower on difficult road sections and faster on easy road sections. Witt and Hoyos suggested follow-up field research in order for the results to be generalized to the real world.(25) After reviewing literature that investigated the potential benefits of transverse stripes as warnings before curves or at stop approaches, Bali et al. considered them to be effective at reducing the average speed and the variability around that average.(24) Bali et al. suggested the use of transverse stripes painted across approach lane(s) at gradually decreased spacing where a required stop is unexpected or in high accident areas. The use of thermoplastics was also suggested (as paint would wear away too fast), along with a bar width of 609.6 mm (24 in) and an overall pattern length of 152.5 m (500 ft).(24) Taylor et al. suggested that the principle of perceptual modification techniques might be applied to spacing of RPMs or PMDs. They thought that deliberate distortions of relative motion between marker and vehicle might produce the deceleration profiles required.(13) Blaauw also suggested relating the spacing of RPMs to road curvature like that used for stripes and PMDs.(17) In fact, a study by Zwahlen (1993) used an optical illusion in an attempt to reduce driver speeds.(26) He arranged PMDs to provide a perceptual illusion of increased curve sharpness by ascending (or descending) delineation heights. The height increments needed to be relatively large (e.g., 1.07 m (3.5 ft) to 1.65 m (5.41 ft) over a 72-m (236-ft) curve length); the results found a reduction in speed with significant center speed reduction from 49.69 km/h (30.88 mi/h) to 44.09 km/h (27.4 mi/h).(26) A study by Rockwell and Hungerford (1979) (cited in Zwahlen, 1993) also found a decrease in speeds through curves when a novel PMD system was used.(26) Further research is needed to determine whether the effect wears off over time.

    There are many coded delineation issues that remain unclear, such as what part of the curve

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(e.g., radius, degree of curvature) reveals the most essential elements of a turn (e.g., sharpness, width) and whether RPMs present this information early enough to warn the driver. The results of a study by Fildes and Triggs highlight a potentially dangerous illusion in the perception of curvature during the negotiation of bends in the road.[7] They found that, when drivers are asked to make judgments about curvature—similar to a situation commonly experienced as a driver moves along a curved two-lane highway—first, the driver will primarily make that judgment on the basis of the curve's deflection angle, and second, the radius of curvature is likely to be misinterpreted by drivers in their assessment. Subjects in the experiment responded to small-radius, small-angled curves as least curved when in fact they were the most curved.[7] Thus, it seems important to ensure that the driver has as much information about the most important part of the curve as far ahead of time as possible. The curve-assessment process was shown by Cohen and Studach (1977), and McLean and Hoffman (1973) (cited in Fildes and Triggs) [7], and by Shinar et al. [4], to start well in advance of the vehicle entering the curve (at least 100 m (327.9 ft) before); far delineation is therefore essential to provide the necessary information.

The above research should be included in a thorough literature review, and further empirical studies should be conducted to answer questions such as: "Does the effect of coded delineation wear off over time?" and "How are accident rates affected by coded delineation?"

24. The Roadway Delineation Practices Handbook lists the following guidelines in the text and refers to figure 50 for clarification of RPM placement in work zones.[2]

RPMs should supplement paint with a spacing of 12.2 m (40 ft) (a retroreflective RPM is placed midway between each 3.05-m (10-ft) paint stripe).

If RPMs substitute painted for skip lines, a cluster of four nonretroreflective RPMs with a retroreflective RPM every 12.2 m (40 ft) or N is recommended. The nonretroreflective RPMs should be placed 1 m (3 1/3 ft) or N/12 apart to provide the daytime appearance of a skip line.

However, both RPM type and spacing are depicted differently in figure 50 than is written in the text. According to the figure, the following guidelines should be used:

RPMs can be used to substitute paint on two-lane, two-way roads if work zones will last 14 days or less. A series of three RPMs will be intra-spaced at N/12 and inter-spaced at 10N/12 (or N distance from the first RPM in series 1 to the first RPM in series 2).

RPMs can be used to substitute paint on two-lane, two-way roads if work zones will last over 14 days. A series of three RPMs will be intra-spaced at N/12 and inter-spaced at 10N/12 (or N distance from the first RPM in series 1 to the first RPM in series 2), and accompanied by painted edgelines.

RPMs can be used to substitute for paint on two-lane, two-way roads with severe curvature if work zones will last 14 days or less. A series of two RPMs are used, intra-spaced at N/20 and

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inter-spaced at 18N/20 (or N/2 distance from the first RPM in series 1 to the first RPM in series 2).

This discrepancy needs clarification. It is also important that the guidelines specify under which circumstances paint should be replaced by RPMs rather than be supplemented by them.

25. Pennell recommended that TRPMs should be spaced at 1.5 m (5 ft) or N/8 with retroreflective units at 6.1 m (20 ft) when substituting stripes.(19) This should be considered when determining which source (text or figures) reflects the guidelines of the Roadway Delineation Practices Handbook.

26. The results of the study by Davis were used to make recommendation for the preferred way to delineate at curves, drop-offs, and relocated ramps. (27) The final recommendations for RPMs were listed in the subsection above; there were also a series of suggested study areas that emerged from the survey of professionals who had delineation experience. Some of these were not included in the final experiments, and may warrant further research. For horizontal and vertical curves, consider supplemental retroreflective RPMs spaced 6.1 m (20 ft) apart or retroreflective RPMs spaced 1.8-3.05 m (6-10 ft) apart when used without paint. For relocated entrance ramps, consider supplemental RPMs spaced at 3.05 m (10 ft) and RPMs spaced at 1.5 m (5 ft) when used without paint.

27. More information is required in order to compile a final list of features that should be incorporated for RPM types. A minimum reflectivity criteria for RPM effectiveness has yet to be established and will influence the level of reflectivity required for new RPMs. Cost analyses will determine whether a minimum half-life is required. Research to determine lens types, damage protectors, mountings and other special features will most likely follow production-driven studies. Documentation of acceptable features should be extrapolated from these sources.

28. Zwahlen explains the use of OCARD (ODOT Computer Aided Road Delineation)—a knowledge-based system that computes the delineation layout using consistent and uniform delineation—in his study "Optimal Application and Placement of Roadside Reflective Devices for Curves on Two-Lane Rural Highways."(26) If it is possible to adapt this software system for the use of RPMs, it may aid the traffic engineer in the application of RPMs and make the task more efficient. The potential of this package should be investigated further.

29. As of yet, there are no national guidelines for when to replace an RPM. Since the criteria for determining minimum acceptable reflectivity for RPMs are not yet resolved, further research must be done in order to set a criterion in place. Currently, individual States determine which criteria to use for replacement procedures, based not on minimum reflectivity but on missing markers. Freedman et al. indicate several States that use different criteria to determine "effectiveness" of RPMs and therefore when to replace them: (3)

California	RPMs are replaced when two or more consecutive markers are missing.
Florida	RPMs are replaced when eight or more consecutive markers are missing.
Texas	RPMs are replaced when 50 percent or more markers are missing within 1.6 km (1 mile) of highway.

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Massachusetts	Replaces only reflective lens if casting is intact.
Michigan	Replaces only reflective lens if casting is intact.
New Jersey	Replaces only reflective lens if casting is intact.
Massachusetts	Snowplowable RPMs are replaced when 30 percent or more markers are missing.
New Jersey	Uses visual inspection.
Pennsylvania	RPMs are replaced as needed, determined by visual inspection.

Since the effectiveness of RPM delineation requires both adequate reflectivity and adequate numbers, it would be ideal to determine a replacement criterion based on both factors. The Delineation Practices Handbook refers to a study by McNees (1987), which sought to determine a procedure that could be used to evaluate the effectiveness of RPM and raised traffic button systems.(31) The evaluating criteria include both reflectivity and loss of markers as indicators of replacement. However, the proposed procedure still requires further investigation. The experimental procedure and, thus, in turn, the proposed evaluation procedure does not account for additional variability.(31) Further research could determine whether evaluations might be biased by factors such as film processing, comparing scenes taken from different cameras or film sets, or whether color film produces significantly different representations from black and white film. Other factors that might bias the contrast or brightness of the photograph should also be investigated, so that a precise procedure might be provided. Lee, Hostetter, and Leibowitz (1991) include some information about controlling for contrast that is useful.(32)

If the method of evaluating photographs proves insufficient, it is still necessary to apply a criterion to determine whether RPMs should be replaced. One issue to consider however, is how one accurately applies such a criterion to RPMs in the field while they are attached to the road. One study addresses some of the problems in measuring wet night performance and discusses the mobile laser retroreflectometer. This measuring device is described as being able to measure background luminance and it records both the coefficient and the contrast luminance of a line along significant distances of road (DeJaiffe, 1987).(33) The progress of this research should be monitored, along with the possibility of measuring RPMs with a mobile device with similar capabilities.

One alternative to measuring reflectivity in the field is to find a relationship between field and laboratory measurements such that laboratory-controlled studies can accurately reflect what would be found in the field. A study by King and Graham (1989) found that there is a strong relationship between test subject subjective evaluation of field luminance and laboratory evaluation of luminance. (34) This relationship can be expressed mathematically and the resulting equation used to calculate "field factors" relating laboratory-produced evaluations to actual field evaluations. If King and Graham's findings can be verified, future research could then be conducted in the laboratory under controlled and safe conditions with minimum field verification. The possibility of applying this method to RPM research should be considered.

30. Given how the luminosity requirements for delineation are outlined (based on research performed by Freedman et al. (3)) in the Roadway Delineation Practices Handbook (2), if possible, the same basic method should be applied to determine minimum contrast levels for RPMs. If a minimum reflectivity criteria cannot be achieved through this method, information from the study by Blaauw and Padmos should be expanded to determine a criterion on the basis of

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visibility distances.[6]

31. If contrast can be used to determine a minimum reflectivity criterion, the results of the computerized headlight evaluation model (DETECT) used by Freedman et al. may be useful.[3] They showed that, for centerline visibility, if a single vehicle providing glare is between 100 and 300 m (327.9-983.7 ft) away, the contrast on dry pavement needs to be eight times greater than when there is no glare source in order to preserve a 3-s preview time. On wet tangents, for a single oncoming vehicle at 300 m (983.7 ft) away, the contrast needs to be four to eight times greater than the contrast needed when there is no glare source to preserve 2 s of preview time.[3]

32. Given that Blaauw and Padmos used a required preview time of 5 s, in clear weather the required preview distance for delineation would have had to be 110 m (360.6 ft) when the velocity was 80 km/h (49.7 mi/h) and 140 m (459 ft) when the velocity was 100 km/h (62.1 mi/h).[6] In fog, the required preview distance for delineation would have had to be 100 m (327.9 ft) when the velocity was 70 km/h (43.5 mi/h) and 110 m (360.6 ft) when the velocity was 80 km/h (49.7 mi/h). According to these findings, at a speed of 80 km/h (49.7 mi/h), the driver would have to be able to see delineation at least 110 m (360.6 ft) ahead in clear weather.[6] If these levels were adjusted using a preview time of 4 s (the upper limit for visibility distance to account for older or impaired drivers) and other conditions were taken into account (e.g., glare), it would be a starting point for determining a minimum reflectivity level based on visibility distance as opposed to contrast level.

33. Consider the progress of research concerning the reflectivity of paint and thermoplastic markings. This will ensure that cost-effectiveness estimates for the use of RPMs is accurately portrayed. Some research studies that may give background or updated information are listed below:

    1. Chapman, B. J. (1994). *Cost-Effective Marking and Delineation Materials for Highways.* Technical Report No. FHWQ-CA-TL-94-06. California State Department of Transportation: Sacramento Division of New Technology, Materials and Research.

    2. Merrit, J. O. and Kerr, S. K. (1977). *Driver's Visibility Requirements for Roadway Delineation, Vol. II: Color Identification of Yellow Highway Paint as a Function of Yellow/White Pigment Mixture Ratio.* Technical Report No. FHWA-RD-77-166. Washington, D.C.: Federal Highway Administration.

    3. Gatlin, G. R. (1993). *Evaluation of Cold Plastic and Hot Spray Thermoplastic on I-20 in Scott County.* Technical Report No. MDOT-RD-93-67-20. Jackson, MS: Department of Transportation.

    4. Kidd, S. Q. (1991). *Cold Plastic and Hot Thermoplastic, Foil-back Tape, Removable Tape and Paint Pavement Markings.* Technical Report No. MSHD-RD-90-67-17. Mississippi State Highway Department, Jackson, MS: Jackson Research and Development Division.

    5. Schrock, M. P. et al. (1993). *Developing a Monitoring System of the Dispensing Rate of Glass Traffic-Line Beads.* Technical Report No. K-TRAN-KSU-92-1. Kansas State University, Manhattan.

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6. Transportation Research Board (1991). *Communications, Traffic Signals, and Traffic Control Devices.* Washington, D.C.: National Research Council.

7. Zwahlen, H. T. and Schnell, T. (1996). Visibility of Yellow Center Line Pavement Markings as a Function of Line Configuration and Line Width. *Proceedings of the Human Factors and Ergonomics Society 40th Annual Meeting.* Ohio University, Athens, Ohio: Department of Industrial and Manufacturing Systems Engineering, pages 919-921.

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7. Fildes, B. N. and Triggs, T. J. (1985). The Effect of Changes in Curve Geometry on Magnitude Estimates of Road-like Perspective Curvature. In *Perception and Psychophysics,* **37**, 218-224.

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