VTRC
Virginia Transportation Research Council

We Bring Innovation to Transportation

Guidance for and Effectiveness of Low-Cost Delineation Treatments

http://www.virginiadot.org/vtrc/main/online_reports/pdf/23-r8.pdf

ALEJANDRA MEDINA FLINTSCH
Senior Research Associate

RONALD GIBBONS, Ph.D.
Program Director

YINGFENG (ERIC) LI, Ph.D., P.E.
Research Scientist

BRIAN WILLIAMS
Research Associate

ANDREW KASSING
Senior Research Specialist

BRADLEY MYERS
Senior Research Specialist

Virginia Tech Transportation Institute

Final Report VTRC 23-R8

VIRGINIA TRANSPORTATION RESEARCH COUNCIL
530 Edgemont Road, Charlottesville, VA 22903-2454
vtrc.virginiadot.org

Standard Title Page - Report on Federally Funded Project

1. Report No.: FHWA/VTRC 23-R8	2. Government Accession No.:	3. Recipient's Catalog No.:
4. Title and Subtitle: Guidance for and Effectiveness of Low-Cost Delineation Treatments		5. Report Date: November 2022
		6. Performing Organization Code:
7. Author(s): Alejandra Medina Flintsch, Ronald Gibbons, Ph.D., Yingfeng (Eric) Li, Ph.D., P.E., Brian Williams, Andrew Kassing, and Bradley Myers		8. Performing Organization Report No.: VTRC 23-R8
9. Performing Organization and Address: Virginia Tech Transportation Institute, 3500 Transportation Research Plaza (0536), Blacksburg, VA 24061		10. Work Unit No. (TRAIS):
		11. Contract or Grant No.: 115051
12. Sponsoring Agencies' Name and Address: Virginia Department of Transportation, 1401 E. Broad Street, Richmond, VA 23219	Federal Highway Administration, 400 North 8th Street, Room 750, Richmond, VA 23219-4825	13. Type of Report and Period Covered: Final Contract
		14. Sponsoring Agency Code:
15. Supplementary Notes: This is an SPR-B report.		

16. Abstract:

Roadway departure crashes (RDCs) occur when a vehicle crosses a centerline, edgeline, or otherwise leaves the intended path of travel. The Virginia Department of Transportation (VDOT) has devoted significant efforts to reducing RDCs. As part of the effort to consider countermeasures, the current project identified best practices in low-cost delineation and data availability through a comprehensive literature review, VDOT district interviews of the current state of practice, and compilation of relevant crash modification factors (CMFs) and effectiveness information. Based on these results, treatments were selected and their effectiveness was evaluated based on Virginia crash sites. Additionally, a human factors study was performed to develop treatment effectiveness and configuration on the rural portion of the Virginia Smart Roads at the Virginia Tech Transportation Institute. The treatments evaluated included curve warning signs (CWS), edgelines, centerlines, post-mounted delineators (PMDs) at 20- and 40-foot spacing, and plastic inlaid markers (PIMs). Finally, the project team also developed a Microsoft Excel-based tool for evaluating benefit-cost ratios (BCRs) based on a range of input variables such as type of facility, annual average daily traffic (AADT), and treatment considerations.

The review of available CMFs showed that, in general, most of the low-cost delineation treatments have a potentially positive effect on reducing crashes, with a few studies showing some potential increase in crash counts for a few countermeasures. The aggregated CMF values suggest that delineators and signs have the highest potential for crash reductions, followed by rumble strips, pavement markings, and raised pavement markers (RPMs).

In the human factors study, participants overwhelmingly selected the PMDs as the most effective treatment. Participant ratings in the human factors study show statistically significant differences between PMDs and other treatments for curve visibility, perceived treatment effectiveness, perceived curve sharpness, and curve awareness. There was no statistical difference among ratings for CWS, edgelines, or PIMs. The two PMD spacings showed more improved performance indicators than the other treatments on many of the measured factors, but the difference was not typically statistically significant.

The benefit-cost analysis toolset developed as part of this project allows engineers to compute BCR not only for all crashes but also for specific crashes depending on the availability of CMFs. The benefit-cost analysis toolset shows significant benefits for all the treatments. As an example, using edgelines on two-lane rural roads with an AADT of 5,000 produces an estimated BCR of between 6.8 and 12.1, assuming a CMF between 0.8 and 0.9. Similarly, a BCR is estimated between 26 and 67 for using PMDs on a 1,000-foot curve with just one RDC each year on average, assuming a CMF between 0.85 and 0.95.

17 Key Words: Delineation, Roadway Departure, Treatment, Guidelines, CMF			18. Distribution Statement: No restrictions. This document is available to the public through NTIS, Springfield, VA 22161.
19. Security Classif. (of this report): Unclassified	20. Security Classif. (of this page): Unclassified	21. No. of Pages: 80	22. Price:

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

FINAL REPORT

GUIDANCE FOR AND EFFECTIVENESS OF LOW-COST DELINEATION TREATMENTS

Alejandra Medina Flintsch
Senior Research Associate
Virginia Tech Transportation Institute

Ronald Gibbons, Ph.D.
Program Director
Virginia Tech Transportation Institute

Yingfeng (Eric) Li, Ph.D., P.E.
Research Scientist
Virginia Tech Transportation Institute

Brian Williams
Research Associate
Virginia Tech Transportation Institute

Andrew Kassing
Senior Research Specialist
Virginia Tech Transportation Institute

Bradley Myers
Senior Research Specialist
Virginia Tech Transportation Institute

VTRC Project Manager
Benjamin H. Cottrell, Jr., P.E., Virginia Transportation Research Council

In Cooperation with the U.S. Department of Transportation
Federal Highway Administration

Virginia Transportation Research Council
(A partnership of the Virginia Department of Transportation
and the University of Virginia since 1948)

Charlottesville, Virginia

November 2022
VTRC 23-R8

DISCLAIMER

The project that is the subject of this report was done under contract for the Virginia Department of Transportation, Virginia Transportation Research Council. The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Virginia Department of Transportation, the Commonwealth Transportation Board, or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation. Any inclusion of manufacturer names, trade names, or trademarks is for identification purposes only and is not to be considered an endorsement.

Each contract report is peer reviewed and accepted for publication by staff of the Virginia Transportation Research Council with expertise in related technical areas. Final editing and proofreading of the report are performed by the contractor.

Copyright 2022 by the Commonwealth of Virginia.
All rights reserved.

ABSTRACT

Roadway departure crashes (RDCs) occur when a vehicle crosses a centerline, edgeline, or otherwise leaves the intended path of travel. The Virginia Department of Transportation (VDOT) has devoted significant efforts to reducing RDCs. As part of the effort to consider countermeasures, the current project identified best practices in low-cost delineation and data availability through a comprehensive literature review, VDOT district interviews of the current state of practice, and compilation of relevant crash modification factors (CMFs) and effectiveness information. Based on these results, treatments were selected and their effectiveness was evaluated based on Virginia crash sites. Additionally, a human factors study was performed to develop treatment effectiveness and configuration on the rural portion of the Virginia Smart Roads at the Virginia Tech Transportation Institute. The treatments evaluated included curve warning signs (CWS), edgelines, centerlines, post-mounted delineators (PMDs) at 20- and 40-foot spacing, and plastic inlaid markers (PIMs). Finally, the project team also developed a Microsoft® Excel™-based tool for evaluating benefit-cost ratios (BCRs) based on a range of input variables such as type of facility, annual average daily traffic (AADT), and treatment considerations.

The review of available CMFs showed that, in general, most of the low-cost delineation treatments have a potentially positive effect on reducing crashes, with a few studies showing some potential increase in crash counts for a few countermeasures. The aggregated CMF values suggest that delineators and signs have the highest potential for crash reductions, followed by rumble strips, pavement markings, and raised pavement markers (RPMs).

In the human factors study, participants overwhelmingly selected the PMDs as the most effective treatment. Participant ratings in the human factors study show statistically significant differences between PMDs and other treatments for curve visibility, perceived treatment effectiveness, perceived curve sharpness, and curve awareness. There was no statistical difference among ratings for CWS, edgelines, or PIMs. The two PMD spacings showed more improved performance indicators than the other treatments on many of the measured factors, but the difference was not typically statistically significant.

The benefit-cost analysis toolset developed as part of this project allows engineers to compute BCR not only for all crashes but also for specific crashes depending on the availability of CMFs. The benefit-cost analysis toolset shows significant benefits for all the treatments. As an example, using edgelines on two-lane rural roads with an AADT of 5,000 produces an estimated BCR of between 6.8 and 12.1, assuming a CMF between 0.8 and 0.9. Similarly, a BCR is estimated between 26 and 67 for using PMDs on a 1,000-foot curve with just one RDC each year on average, assuming a CMF between 0.85 and 0.95.

FINAL REPORT

GUIDANCE FOR AND EFFECTIVENESS OF LOW-COST DELINEATION TREATMENTS

Alejandra Medina Flintsch
Senior Research Associate
Virginia Tech Transportation Institute

Ronald Gibbons, Ph.D.
Program Director
Virginia Tech Transportation Institute

Yingfeng (Eric) Li, Ph.D., P.E.
Senior Research Associate
Virginia Tech Transportation Institute

Brian Williams
Research Associate
Virginia Tech Transportation Institute

Andrew Kassing
Senior Research Specialist
Virginia Tech Transportation Institute

Bradley Myers
Senior Research Specialist
Virginia Tech Transportation Institute

INTRODUCTION

A roadway departure crash (RDC) occurs when a vehicle crosses a centerline or edgeline or otherwise leaves the intended path of travel. To reduce crashes, RDC countermeasures must keep vehicles on the road, provide for safe recovery, and/or minimize crash severity. Low-cost countermeasures for RDCs have low initial and maintenance costs. Such countermeasures can be classified into delineation, signing, and roadside improvement categories. The selection of countermeasures is a complex process. Countermeasure effectiveness depends on many factors, including roadway classification, traffic, environment, roadway geometry, horizontal and vertical curvature, number of lanes, speed limit, the presence of other countermeasures, and installation and maintenance practices. In addition, countermeasure effectiveness varies when different types of crashes are considered. Cost and maintenance are also significant considerations when selecting countermeasures. Thus, it remains challenging to determine when and where to apply countermeasures and to select an appropriate countermeasure configuration and material type. It is also difficult to evaluate the effectiveness of countermeasures given the lack of data and existing installation sites to study. Finally, observational efforts do not incorporate factors like visibility, which are expected to become increasingly relevant in the future as the population ages.

PURPOSE AND SCOPE

To facilitate countermeasure selection and maximize the benefits of limited resources, it is important to develop guidelines for countermeasure selection that consider all of the above factors. The specific objectives of this research project were to:

1. Evaluate the likely safety effects of different low-cost delineation and marking strategies with regard to preventing RDCs; and
2. Determine the life-cycle costs of different effective countermeasures identified under the first objective.

The original scope of this project focused on edgelines with different widths and materials, post-mounted delineators (PMDs) with different materials and spacings, and raised pavement markers (RPMs). During the project, however, additional delineation treatments were included based on input from both the Virginia Department of Transportation (VDOT) project technical review panel (TRP) and VDOT district officials. The types of treatments included in each task of this project are described in more detail in the Methods section.

METHODS

Overview of Research Approach

This project included the following major activities:

- Identify best practices in low-cost delineation and data availability. This effort involved a comprehensive literature review, interviews with VDOT districts on the current state of practice, and compilation of relevant crash modification factors (CMFs) and effectiveness information. The information was presented in an interim report to VDOT.

- Select high-priority treatments to evaluate. During this activity, the project team polled all panel members to identify high-priority delineation treatments to be studied as part of the field effectiveness evaluation and driver behavior testing.

- Develop CMFs based on Virginia data for high-priority treatments. During this project, the team attempted to develop CMFs for two selected delineation treatments based on districts' input: curve warning signs (CWS) with flashing beacons and sequential chevron signs. However, due to the limited number of sites available, the project team could not develop statistically significant CMFs for both types of treatments. This effort is therefore not discussed further in the remaining sections of this report.

- Conduct a human factors study to measure treatment effectiveness and develop configuration guidelines. The human factors study was conducted on the rural portion of the Virginia Smart Roads at the Virginia Tech Transportation Institute (VTTI).

- Conduct life-cycle benefit-cost analysis of low-cost delineation treatments. As part of this activity, the project team developed a Microsoft® Excel™-based tool for evaluating benefit-cost ratios (BCRs) based on a range of input variables such as type of facility, annual average daily traffic (AADT), and treatment considerations.

The following subsections offer more detail on the approaches and procedures used for the major activities outlined above. The outcomes of each of these efforts are presented in the results section of the report.

Identify Best Practices in Low-Cost Delineation and Data Availability

The team conducted district interviews to understand current practices, needs, and the issues and challenges relevant to low-cost delineation measures. The researchers sent invitations for a telephone interview to traffic engineering staff of all nine VDOT districts and were able to talk to officials from eight districts. Prior to each interview, the project team sent out a list of questions to guide the discussions (shown in Appendix A). The interviews centered on how delineation treatments are selected at the district level, identification of systemic delineation treatments, identification of enhanced or alternative treatments, maintenance, study sites, and data availability. Each interview was scheduled for 1 hour with the actual interviews lasting from 45 minutes to 1 hour and 15 minutes. All interviews were conducted online with options to access via conference call.

Part of this task was also to identify high-priority treatments for further evaluation during the human factors study. For this purpose, the project team took the following steps:

- Identify candidate low-cost delineation treatments based on a literature review and panel input.
- Poll VDOT districts for needs, priority, and usage of the candidate treatments.
- Compare CMF availability with district survey results.
- Finalize treatments for further evaluations, including the field data analysis and the human factors study on the Smart Roads Rural Roadway Expansion.

Review CMF Availability

During the district interviews, VDOT personnel expressed the need to stay updated about the latest CMFs and availability of the CMFs for the studied delineation treatments. This is especially true when they need to select a treatment for specific cases or specific conditions. The research team conducted an in-depth evaluation of the CMFs corresponding to the various low-cost delineation countermeasures studied. The review of national CMFs was primarily based on the CMF Clearinghouse while the review of VDOT-preferred CMFs was based on a comprehensive literature review of Virginia-specific studies and VDOT websites relevant to curve delineation. The results helped the research team better understand the safety effectiveness of the low-cost delineation treatments studied in this project and collect CMF information for the benefit-cost analysis toolset development.

Development of a Benefit-Cost Analysis Toolset

Overview of the Benefit-Cost Toolset Approach

During the VDOT district interviews, multiple districts expressed the need for a tool that would allow VDOT engineers to prioritize or select the most suitable low-cost delineation treatments based on roadway conditions with consideration of the BCRs and their effectiveness. For segment/network-level applications, the project team used safety performance functions (SPFs) for RDCs from a recent VDOT project (Kweon & Lim, 2019). Table 1 lists the types of facilities this task considered. Table 2 and Table 3 list the detailed SPFs.

Table 1. Roadway Types Considered in this Study (Kweon & Lim, 2019)

Site Type	Site Type Description
101	Rural 2-lane segments
102	Rural multilane undivided segments
103	Rural multilane divided segments
151	Urban 2-lane arterial segments
152	Urban multilane undivided arterial segments
153	Urban multilane divided arterial segments

Table 2. SPFs for All RDCs (Kweon & Lim, 2019)

Site Type	SPF
101	$N_{SPF} = exp[-5.570 + 0.621 \times ln(AADT) + ln(Length)]$
102	$N_{SPF} = exp[-1.029 + 0.00004868 \times AADT + ln(Length)]$
103	$N_{SPF} = exp[-10.16 - 0.00005996 \times AADT + 0.0000000006292 \times AADT^2 + 1.148 \times ln(AADT) + ln(Length)]$
151	$N_{SPF} = exp[-8.939 - 0.0001376 \times AADT + 0.000000001541 \times AADT^2 + 1.095 \times ln(AADT) + ln(Length)]$
152	$N_{SPF} = exp[8.378 - 0.0001526 \times AADT + 0.000000001076 \times AADT^2 - 3.522 \times ln(AADT) + 0.298 \times (ln(AADT))^2 + ln(Length)]$
153	$N_{SPF} = exp[-5.275 + 0.534 \times ln(AADT) + ln(Length)]$

N_{SPF} = number of predicted crashes, $AADT$ = average annual daily traffic.

Table 3. SPFs for Fatal and Injury RDCs (Kweon & Lim, 2019)

Site Type	SPF
101	$N_{SPF} = exp[-10.510 + 1.859 \times ln(AADT) - 0.0891 \times (ln\ (AADT))^2 + ln(Length)]$
102	$N_{SPF} = exp[-5.123 + 0.421 \times ln(AADT) + ln(Length)]$
103	$N_{SPF} = exp[-6.929 + 0.647 \times ln(AADT) + ln(Length)]$
151	$N_{SPF} = exp[-10.48 - 0.0001414 \times AADT + 0.000000001482 \times AADT^2 + 1.174 \times ln(AADT) + ln(Length)]$
152	$N_{SPF} = exp[-11.60 - 0.00003927 \times AADT + 1.181 \times ln(AADT) + ln(Length)]$
153	$N_{SPF} = exp[-5.908 + 0.510 \times ln(AADT) + ln(Length)]$

N_{SPF} = number of predicted crashes, $AADT$ = average annual daily traffic.

The toolset was developed using the Microsoft Excel platform. The toolset allows the calculation of a range of BCRs based on user-selected treatments, AADT, facility type, crash severity level, and CMF ranges. A detailed description of the benefit-cost analysis toolset and the benefit-cost information used is included in Appendix B. Note that this toolset was developed as a prototype demonstrating the idea of using BCRs to prioritize low-cost delineation treatments in cases when multiple treatments can be used.

Benefit-Cost Analysis Methodology

To understand the potential safety benefits of the low-cost delineation treatments, the project team conducted a benefit-cost analysis for rumble strips, edge/centerlines, curve warning message markings (word, symbol and arrow markings that warn of the curve), PMDs, chevrons, a curve warning sign (CWS) with flashing beacons, sequential chevron curve warning systems, RPMs, PIMs, and safety edge based on the original project scope and additional feedback from the project panel.

During this benefit-cost analysis, the project team only considered safety benefits, as these are the most dominant benefits for delineation devices, particularly on roadways with limited AADT. The safety BCR is defined as the ratio between the benefits and costs in the same dollar terms:

$$BCR = \frac{PVB}{PVC}$$

Where:
BCR = safety BCR;
PVB = present value benefit; and
PVC = present value cost.

In the equation above:

$$PVB = \sum_{t=0}^{LC} \sum_{j} PC_{j,t},\ \ j \in \{K, A, B, C, O\};\text{ or}$$

$$PVB = \sum_{t=0}^{LC} PC_t \text{ if average crash cost (regardless of severity is used)}$$

Where:

$PC_{j,t}$ = the total potential costs of severity *j* crashes prevented in year *t* in current year dollars by the infrastructure category;

PC_t = the total potential costs of all crashes (regardless of crash severity) prevented in year *t* in current year dollars by the infrastructure category;

LC = life cycle of the infrastructure category.

$$PC_{j,t} = \left(\frac{1}{(1+r)^t}\right) PC_{j,0},\ j \in \{K, A, B, C, O\};\text{ or}$$

$$PC_t = \left(\frac{1}{(1+r)^t}\right) PC_0 \text{ if average crash cost is used (regardless of severity is used)}$$

Where:

r = discount rate. The Office of Management and Budget currently recommends a discount rate of 7% for long-life projects in benefit-cost analyses relevant to public investment and regulatory decisions (OMB 2018 and USDOT 2017). Other publications typically recommend a rate between 3% and 7% (AASHTO 2015, Gates and Noyce 2005, Appiah and Cottrell 2015, and Lawrence et al. 2018). Following the Office of Management and Budget recommendation, this study used a discount rate of 7%.

$PC_{j,0}$ = potential costs of severity *j* crashes prevented by the infrastructure category during year 0 (i.e., current year) in current year dollars.

PC_0 = potential costs of all crashes prevented by the infrastructure category during year 0 (i.e., current year) in current year dollars.

$$PVC = IC + \sum_t AMC_t$$

Where:

IC = installation cost for the infrastructure category in 2016 dollars.

AMC_t = the present value of the annual maintenance costs for the infrastructure category at year *t*, which is determined by applying the discount rate *r* to the original annual maintenance cost at year *t*, or AMC_o:

$$AMC_t = (\frac{1}{(1+r)^t})AMC_0$$

Combining the equations listed above, the safety BCR for a given safety treatment can be calculated as:

$BCR = \frac{PVB}{PVC} = \frac{PC_0\left[\frac{(1+r)^n-1}{r(1+r)^n}\right]}{IC+AMC_0\left[\frac{(1+r)^n-1}{r(1+r)^n}\right]}$ if average crash cost is used (regardless of severity is used), or,

$$BCR = \frac{PVB}{PVC} = \frac{\sum_j PC_{j,0}\left[\frac{(1+r)^n-1}{r(1+r)^n}\right]}{IC+AMC_0\left[\frac{(1+r)^n-1}{r(1+r)^n}\right]}, j \in \{K, A, B, C, O\}$$

The costs of the prevented crashes were computed as the number of prevented crashes multiplied by crash unit costs (either by crash severity/type or for all crashes). To obtain estimates of potential crashes prevented by a safety treatment, one may use a combination of field crash data, SPFs, and CMFs. If field crash data are used:

$$CR_P = N_o(1 - CMF)$$

Where:

CR_P = potential crashes prevented by the safety treatment. The prevented crashes can be estimated for individual severity levels, individual or combinations of crash types, or all crashes regardless of severity and/or type based on the CMFs used.

N_o = original crash counts for the crashes of the applicable severity and/or level to be estimated before the safety treatment is applied.

In cases where field crash data are not available:

$$CR_P = N_{o,SPF} \times (1 - CMF)$$

Where:

$N_{o,SPF}$ = original crash counts estimated using a Virginia SPF. If a Virginia version of the SPF for the site condition is not available, the user may use a suitable national SPF or apply a calibration factor (C) to estimate the original crash counts before the safety treatment is applied:

$$CR_P = N_{o,SPF} \times C \times (1 - CMF)$$

To conduct the benefit-cost analysis, the project team first compiled crash costs and the costs associated with the installation and maintenance of the delineation treatments. The cost data compilation was based primarily on two sources: information collected via a comprehensive literature review and bid data from VDOT.

Note that, the safety benefits of this toolset for segment treatments relied on crashes predicted based on VDOT SPFs, while the tools for spot treatments relied on observed crashes. This approach is a simplified approach without requiring both predicted and observed crashes at the same time and the adjustment based on the Empirical Bayes method. To maximize flexibility, the simplified tools were developed to accommodate all different site conditions (e.g., lane numbers, alignment, and traffic). The SPFs and CMFs are frequently unavailable based on the specific site conditions to be analyzed. Due to this reason, the team did not include very specific analysis scenarios for each tool.

The segment tools were developed for the purpose of estimating safety benefits for an average roadway segment should the treatment be considered for a systemic implementation. The analyst may or may not have access to historical crash data for the analysis segment. The tools used a default segment length of 10 miles, which is relatively long with a small overdispersion parameter. Users should note that, the 10-mile length was used for the purpose of improving reliability of the VDOT-developed safety performance functions used in the tools. This length is a factor for both crash prediction and cost calculation. Changes in the segment length therefore does not affect the benefit-cost ratio calculations. The weighted adjustment factor therefore should be close to one, leading to a trivial adjustment to the predicted crashes.

As previously stated, the project team developed this simplified toolset as a prototype to demonstrate the idea of using such a tool to aid the selection of the most cost-effective treatments. While comparing different treatments for the same application type (i.e., segment versus spot), the crash base should be the same no matter if predicted or observed crashes are used. Due to this reason, whether the crashes are adjusted or not would not affect the results. If desired, the toolset may be improved with enhanced functionality to accommodate more sophisticated crash analysis methods, expand the collection of treatments, provide more detailed CMF options and scenarios, and improve the user interface and result presentation.

Human Factors Study Design

Test Track

The Virginia Smart Roads Rural Roadway is a unique testing facility designed to recreate the challenges of rural roads, which account for two-thirds of all roadways in the United States. The facility includes hilly and flat winding roads with limited sight distances, natural foliage, narrow sections, soft grass shoulders, and rural intersections. An aerial view of the Rural Road is shown in Figure 1, with numbers denoting the locations where the curve warning and/or delineation treatments were installed.

Figure 1. Aerial View of the Virginia Smart Roads Rural Roadway. Numbers represent the curves where treatments were applied. Curve characteristics are summarized in Table 4.

Delineation treatments were applied at seven different curves along the test track (numbered in Figure 1 above). Table 4 lists the length and radius of each curve and other characteristics of note.

Table 4. Curve Characteristics

Curve #	Length (ft)	Radius (ft)	Notes
1	151	160	Contiguous with Curve 2
2	241	215	Contiguous with Curve 1
3	134	80	Existing edgelines and centerlines
4	204	95	Includes vertical curvature
5	210	300	Ill-defined pavement edge on inside of curve
6	103	70	Includes vertical curvature
7	365	250	No existing markings; Adjacent to an intersection

Specific aspects make each curve unique. Curves 1 and 2 are adjacent to each other; when traveling in the outer lane, no true tangent exists before the curve. Curves 4 and 6 include vertical curvature in which the outer lane has a downhill slope and the inner lane an uphill slope. One end of Curve 7 meets an intersection, and it includes vertical curvature in which the outer lane travels uphill and the inner lane downhill. These characteristics will come into play when discussing the results of the study.

To examine the effect of treatments across different curve lengths and radii, the curves were divided into different length and radius categories in some analysis scenarios. Table 5 shows how each curve was categorized by length and radius. Please note that the categories used are relative to the curves available to the research team on the Rural Roadway Expansion and are not representative of all curves on Virginia roadways. For example, a "large" curve in this study is relatively small compared to other curves on public roadways.

Table 5. Curves Categorized by Length and Radius

Length Category (L, in ft)	**Radius Category (R, in ft)**		
	Smaller	**Medium**	**Larger**
Shorter	Curve 3 (L: 134, R: 80) Curve 6 (L: 103, R: 70)	Curve 1 (L: 151, R: 160)	-
Medium	Curve 4 (L: 205, R: 95)	-	Curve 5 (L: 210, R: 300)
Longer	-	Curve 2 (L: 241, R: 215)	Curve 7 (L: 365, R: 250)

While these categories allowed the research team to investigate the effect of treatments relative to the length and radius of the curves, it is important to note some anomalies in this grouping. For example, the "Short" length and "Small" radius categories include Curve 3, which had edgelines with all treatments. Additionally, "Large" radius curves included Curve 5, in which the speed is affected by nearby curves, and Curve 7, which has no centerline. Due to these issues and the relatively small sizes of these curves compared to those on public roads, results by length or radius category should be interpreted cautiously.

Test Vehicles and Equipment

Participants drove a 2017 Ford Explorer sport-utility vehicle (Figure 2) equipped with a data acquisition system (DAS). The DAS recorded data from the vehicle network as well as video from four onboard cameras and differential GPS data, among other data. These data were later reviewed using VTTI's proprietary software called Hawkeye (Figure 3).

Figure 2. 2017 Ford Explorer Driven by Participants (Left) and Data Acquisition System (Right).

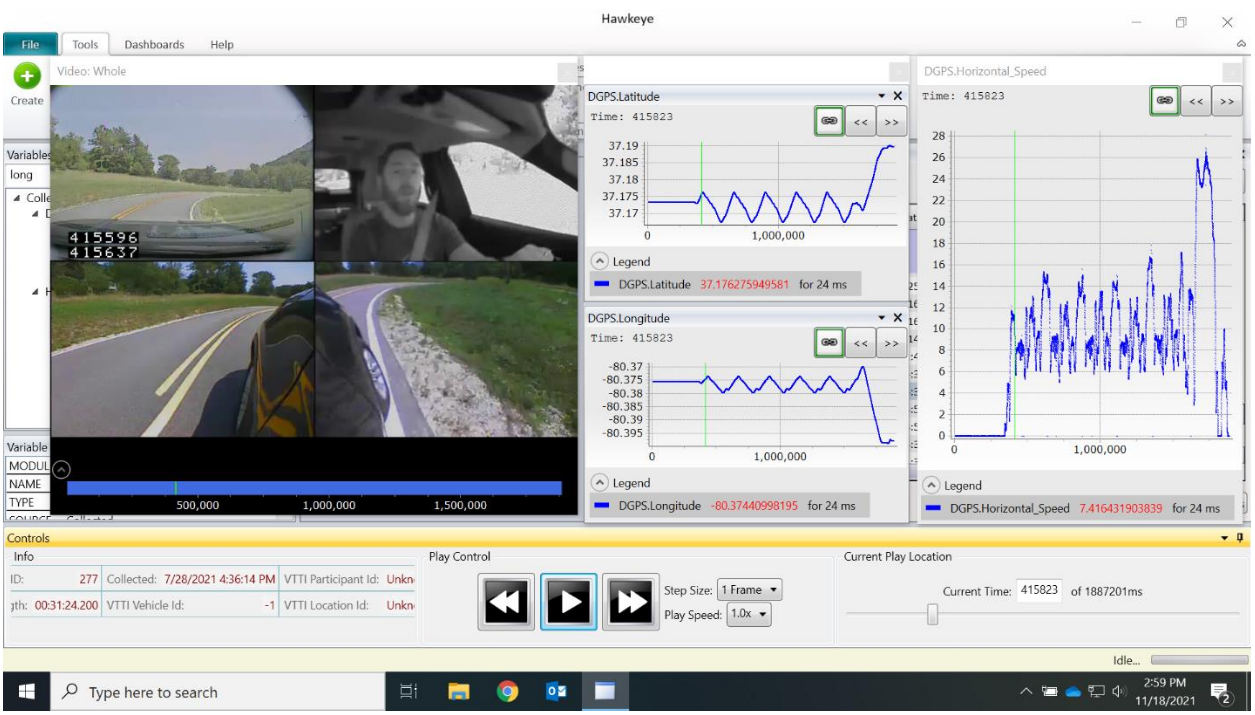


Figure 3. DAS Data Viewed through the Hawkeye Software.

Treatment Scenarios

Based on the research team's review of potential low-cost delineation systems and the polling results of VDOT district traffic engineers and the TRP (Appendix A), four different treatments were selected for the human factors study. These included CWSs, edgelines, plastic in-laid markers (PIMs), and PMDs. For PIMs, markers were placed on the surface, not in-laid. The PIMs were installed in the center of the road and spaced 40 feet apart. The CWSs were installed 100 feet before the start of each curve with the bottom of the sign 5 feet above ground level. The PMDs were installed on the outside of the curve approximately 4 feet from the edge of the pavement and were spaced either 20 feet or 40 feet apart. Additionally, a baseline condition was included for each curve, which means six different conditions were examined.

Figure 4. Example Photos of PMDs (Left) and a CWS (Right).

The baseline conditions were not the same for all curves. Curves 1, 2, 4, 5, and 6 each had an existing double yellow centerline as the baseline condition. However, Curve 3's baseline condition included white edgelines in addition to a double yellow centerline. Curve 7 was the only curve that did not have any existing markings, so the baseline condition was no treatment. Each of the selected treatments was added to these baseline conditions, resulting in different combinations of treatments. Table 6 lists the specific treatment combinations for each curve based on the assigned treatment.

Table 6. Treatment Combinations for Each Curve Based on the Baseline and Assigned Treatment

Curve	**Treatment**					
	Baseline	CWS	Edgelines	PIMs	PMD 20	PMD 40
1, 2, 4, 5, 6	Centerline	Centerline + CWS	Centerline + Edgelines	Centerline + PIMs	Centerline + PMD 20	Centerline + PMD 40
3	Centerline + Edgelines	Centerline + Edgelines + CWS	Centerline + Edgelines	Centerline + Edgelines + PIMs	Centerline + Edgelines + PMD 20	Centerline + Edgelines + PMD 40
7	None	CWS	Edgelines	PIMs	PMD 20	PMD 40

CWS = Curve Warning Sign, PIM = Plastic Inlaid Marker, PMD = Post-mounted Delineator.

On-pavement curve warning received a high priority for evaluation by district traffic engineers and the TRP. The TRP decided not to include them in this evaluation and recommended evaluating them in a possible second phase.

Participants

A total of 48 participants took part in the study. Participants were between the ages of 18 and 65 and were required to have a valid driver's license and a minimum visual acuity of 20/40, which is the minimum required to have a driver's license in Virginia.

Participants were divided into six groups of eight. Each group of participants observed different treatments on each curve. Treatments were balanced across groups so that each participant saw each treatment at least once and each treatment was seen on each curve once. The only exception was the edgelines condition. Because the edgelines could not be easily removed once they were painted, this condition was saved for the last group. Table 7 shows which treatments were installed on each curve for each participant group.

Table 7. Participant Groups and Curve Treatments

Participant Group	**Treatment**						
	Curve 1	Curve 2	Curve 3	Curve 4	Curve 5	Curve 6	Curve 7
1	Baseline	Baseline	CWS	PIMs	PMD 20	PMD 20	PIMs
2	CWS	CWS	Baseline	PMD 40	PIMs	Baseline	PMD 20
3	PIMs	PIMs	PMD 20	Baseline	PMD 40	PMD 40	CWS
4	PMD 20	PMD 20	PMD 40	CWS	Baseline	PIMs	PMD 40
5	PMD 40	PMD 40	PIMs	PMD 20	CWS	CWS	Baseline
6	Edgelines	Edgelines	Edgelines	Edgelines	Edgelines	Edgelines	Edgelines

CWS = Curve Warning Sign, PIM = Plastic Inlaid Marker, PMD = Post-mounted Delineator.

Experimental Procedure

Initial Contact

Participants were contacted via telephone and read a brief description of the study. Those that were interested in participating were screened to ensure they met the eligibility criteria. Those that were eligible were scheduled to come to VTTI for their session and were sent an email, which included a copy of the informed consent form to review prior to their scheduled session.

Consenting

Participant sessions were scheduled to take place after dark (approximately between 9:00 p.m. and midnight). When participants arrived at VTTI, they were greeted by an experimenter and taken to a participant prep room, where they signed the consent form, completed other paperwork, and performed a Snellen visual acuity test. An experimenter then read a brief description of the study tasks and escorted the participant to the experimental vehicle.

Smart Road Tasks

The experimenter oriented the participant to the vehicle controls and had them adjust the seat and steering wheel to comfortable positions and buckle their seat belt. The experimenter then entered the back seat of the vehicle and prepared the data collection equipment. The participant was then instructed to drive to the test track. COVID-19 protocols were followed at all times.

Once participants were on the Rural Roadway, the experimenter had them stop the vehicle and read the in-vehicle script:

> *"In just a moment, I'll have you begin the study by driving straight ahead along this road. The maximum speed limit for tonight is 30 mph, but this test track includes a lot of turns and hills which will require you to adjust your speed accordingly. You do not need to try to maintain 30 mph; just drive at a comfortable speed and do not exceed 30 mph. Does that make sense?*

This test track also includes several intersections, but unless I say otherwise, just continue on the road that you're on. As a reminder, we may encounter deer or other wild animals as we drive so be prepared to respond if needed.

Do you have any questions before we begin?"

The wording of the script was selected to ensure participant safety by providing a maximum speed limit and letting them know that the course included sharp curves. The script was also intended to minimize the impact of the instructions on participant behavior by giving them enough freedom to select their own speed through the curves.

Participants then drove four laps around the test track as the experimenter provided directions. Every other lap, participants alternated the direction they drove through the curves so that they drove through each curve twice in the inner lane and twice in the outer lane. This alternating pattern was also used to prevent participants from learning the test track so that their behavior in the curves would be based more on the treatments and less on their memory of the roadway.

Once the four laps were complete, the participant answered survey questions about each curve. The experimenter instructed the participant to stop the vehicle on the approach to each curve. While looking at the curve and the treatment, the participant answered the questions shown in Figure 5.

Once the participant answered all four questions, they were instructed to pull up to the next curve and repeat the process until they had answered the questions for all seven curves. Participants were then asked one final question before being taken back to VTTI, where they were compensated and released:

"Tonight, you drove through several curves with the assistance of several treatments. These included white lines on the edge of the pavement, yellow curve warning signs, reflectors on the road surface, and reflective posts along the outside of the curve. Of these 4 treatments, which do you think was most helpful?"

Regarding the curve that we are currently looking at…

1) Using a scale from 1 to 5 where 1 means you can't see it at all and 5 means you can see it very clearly, how well can you see the curve ahead?

1	2	3	4	5
Can't see it at all				See it very clearly

2) Using a scale from 1 to 5 where 1 is "not sharp" and 5 is "very sharp", how sharp would you say this curve is?

1	2	3	4	5
Not sharp				Very sharp

3) Using a scale from 1 to 5 where 1 is "not effective" and 5 is "very effective", how effective do you think the [sign/reflectors/white lines] is/are at preparing you for the curve?

1	2	3	4	5
Not effective				Very effective

4) What do you think the maximum safe speed for this curve should be?

Figure 5. Survey Questions.

Data Collection, Reduction, and Analysis

During the experiments, the project team collected the following datasets:

- *Survey data.* The survey data consisted of the number ratings of the curve visibility, curve sharpness and treatment effectiveness, and the maximum safe speed. It also included the treatment that participants chose as the most effective. The rating data were evaluated using an analysis of variance (ANOVA) produced with a generalized linear modeling method. The significance level was set at 0.05. Post hoc comparisons between factor levels were done using a difference of least squared means procedure. The safe speed data were analyzed using simple descriptive statistics. The selection of the most effective treatment was analyzed as a simple count of the number of times a treatment was selected compared to the others.

- *Lane violation data.* A data reductionist watched the video recorded for each participant and logged each time the participant's left front tire crossed over the double yellow centerline within a curve. These data were analyzed using simple descriptive statistics.

- *Driver behavior data.* The driver behavior data collected using the DAS included detailed three-dimensional speed and acceleration data at a frequency of 10 hertz for each entire participant trip. This dataset was processed into two types of data:

- *Point-based data*. Instantaneous speed and acceleration data from the vehicle's DAS were sampled at specific points along each curve each time a participant drove through it. This allowed the research team to analyze participant speed at specific points before and within the curve. For each curve, the team used four points for this purpose: 100 feet before the curve start, curve start or entry point, middle point, and end point.
- *Full-curve data.* Continuous data collected by the vehicle's DAS from the moment a participant entered a curve until they exited the curve were examined. This allowed the research team to analyze how participant behavior varied within a curve.

Both the point-based and full-curve datasets were analyzed using a mixed modeling for repeated measures procedure. The significance level for all statistical tests was set at $\alpha = 0.05$. Post hoc analysis was done using a difference of least squared means procedure.

RESULTS

VDOT District Practices Relevant to Low-Cost Delineation

The following section summarizes the major feedback gathered from the district interviews related to the use of low-cost delineation measures. Interviews were conducted over a period of two months in 2019 and were based on VDOT policies in place at the time. Some policies may have changed since the interviews were conducted.

RDC Severity, Contributing Factors, and Locations of Concern

All district officials suggested that RDCs were a major safety concern for the districts. In most districts interviewed, RDCs were responsible for more than half of the deaths due to traffic crashes. The district officials suggested the following:

- Most district officials believed that high speed, rural locations, curves, and lack of shoulder were the common factors correlated with RDCs. Driver distraction and fatigue frequently contribute to roadway departures as well. Some district officials also suggested that adverse weather conditions in many cases cause roadway departures. Although curved roadway segments tended to have a higher risk for roadway departures, some districts also observed RDCs on straight roadway segments, particularly those that follow a relatively long section of curved roadway.

- Many districts indicated that RDCs were common on almost all types of roadways, including freeways, primary roadways, and secondary roadways, as long as the perceived contributing factors are present. However, districts agreed that higher-volume routes such as freeways and multilane arterials generally have shoulders and are better funded. Therefore, districts generally considered two-lane primary and secondary roadways as locations deserving more safety measures. Table 8 lists the types of roadways suggested by the district officials to focus on during this research project.

Table 8. List of Roadway Types Suggested by District to Study

District	Suggested Focus
Bristol	Primary two-lane highways
Culpeper	Higher volume secondary roadways
Fredericksburg	High-risk rural roadways
Hampton Roads	Secondary two-lane roadways
Lynchburg	District currently focuses on four-lane primary first and two-lane primary second, but secondary roadways need attention as well
Northern Virginia	Two-lane undivided rural roadways with higher speed and volume
Richmond	Rural roadways, including rural roadways with narrow right of way and no shoulders
Salem	Primary roads- higher volume speed
Staunton	Undivided two-lane roadways based on functional class

Delineation Treatment Selection and Design

The districts interviewed mostly suggested that there is not a systemic approach to determine where and what low-cost delineation treatments are used. In general, the selection and implementation of low-cost delineation measures are based on Central Office policies, district policies, and/or engineering judgement at the project level. Some districts may use available CMFs to facilitate the decision-making process at the project level. None of the districts interviewed conducted benefit-cost analysis on a regular basis, believing that any severe crashes reduced by the low-cost treatments would greatly outweigh the costs. For safety projects, however, districts typically use crash history as the most important factor for justifying the needs of safety treatments.

The district officials discussed the following low-cost delineation treatments during the interviews:

- Rumble strips. The VDOT Traffic Operations Division (TOD) has pushed statewide the systemic use of rumble strips as a low-cost treatment for RDCs. Following this policy, many districts are implementing shoulder rumble strips on a wide scale following the paving schedules. Note that many secondary roadways do not have shoulders where shoulder rumble strips can be installed. In addition, due to noise issues, some districts avoid using shoulder rumble strips in residential areas. Based on the district interviews, centerline rumble strip practices differ significantly among districts. Some districts install centerline rumble strips extensively, while others use them on a very limited scale.

  During the systemic implementation of rumble strips, districts typically select roadways either based on roadway type or by following specific criteria. For example, some districts are installing rumble strips on all primary roadways, while others also implement them on all two-lane roadways with a 45-mph or higher speed limit. Some districts are also looking at locations on higher volume secondary roadways with historical RDCs for rumble strip implementations. Mumble strips are also being piloted in some districts.

- Chevron signs. Chevron signs are another roadway departure treatment commonly used by districts. The use of chevron signs is also limited by the availability of shoulders. Some roadways in mountainous areas do not have any shoulder to accommodate posts for chevron signs. In addition, to install chevron signs individually, some districts also mount them on guardrails to improve safety. All districts follow the *Manual on Uniform Traffic Control Devices* (MUTCD) requirements when selecting and installing chevron signs.

- RPMs. In August 2019, VDOT decided that cast iron snow-plowable raised pavement markers (SRPMs) will no longer be installed on VDOT projects throughout the Commonwealth. In lieu of SRPMs, VDOT began using Plastic Inlaid Makers (PIMs). Since RPMs were present in various parts of the network before 2019, RPMs were included in the interview. The districts in general used RPMs on the centerlines of primary roadways with relatively high speed limits (e.g., 45 mph or higher) and high volume. The interviewed districts suggested that RPMs were rarely used on edgelines. A few districts noted the used of RPMs at intersections to improve their conspicuity. The officials interviewed during the project mentioned some examples of RPMs on edgelines, most of which, however, were in areas where fog and other adverse weather conditions are frequently present. PMDs. PMDs are generally not widely used in the districts. Some districts indicated that tube delineators were used at some locations but not systemically. Decisions to use PMDs are generally made on a case-by-case basis. Other districts install PMDs at locations where guardrails are warranted but there is insufficient space to install them.

- Centerline/edgeline pavement markings. Most districts seldom use centerlines/edgelines as additional delineation treatments. The use of pavement markings is generally determined based on the MUTCD and the VDOT supplement to MUTCD. Many secondary roadways do not have edgelines. Such roadways are typically narrow with no shoulders on both sides. A district indicated that they are in the process of implementing 6-inch edgelines for all primary roadways. Another district suggested that water-based markings could be particularly effective during nighttime.

- Cable barriers. Some districts indicated cases where roadside cable barriers are used to prevent roadway departures.

In addition to the aforementioned low-cost treatments, some districts are adding shoulders when possible to roadway segments where RDCs are a major concern. The districts also mentioned the use of guardrails to prevent severe RDCs. However, both guardrails and shoulder installations are much more costly compared to low-cost solutions. Beginning February 2020, VDOT required that all new paving projects include safety edge (shoulder wedge) if certain criteria are met. On a case-by-case basis, some districts also use oversized signs, LED signs, or Intelligent Transportation System signs to warn drivers of dangerous curves.

District Needs to Assist in Decision-making

The districts interviewed during this project were generally divided when asked about guidelines or tools to help engineers identify the most cost-effective treatments for RDCs. Some district officials suggested that the districts have sufficient knowledge and tools for making decisions relevant to delineation treatments, citing in-house engineering experience, Central Office assistance, and available tools such as *Highway Safety Manual* and MUTCD. Others felt that additional help would be beneficial, particularly when selecting the most cost-effective treatments or treatment combinations in scenarios where multiple options seem to be viable. In many cases, although all are considered low cost, there are major cost differences among commonly used treatments such as rumble strips, chevron signs, and wider pavement edgelines. The district officials indicated a need to know, for given roadway settings, if a lower-cost treatment would be sufficient in preventing roadway departures. In addition, some districts indicated a need for guidelines to identify the most effective measures on two-lane roadways without shoulders.

Some districts also suggested a need to review and rank the relevant national and VDOT CMFs for different scenarios to facilitate the districts in selecting the best CMFs for a given scenario.

Maintenance of Low-Cost Delineation Devices

Some districts considered the limited maintenance budget and staffing availability as a factor hindering the implementation of some delineation treatments. For example, although initial installation costs are low for chevron signs, RPMs, and, to a lesser extent, pavement markings, such installations all need to be maintained periodically. The limited maintenance resources at districts are typically focused on primary roadways, and therefore some districts can be hesitant when implementing such treatments on secondary roadways due to maintenance concerns. Rumble strips, on the other hand, require little maintenance, which is an important factor for their popularity at many districts.

Depending on staff availability, some districts routinely inspect and maintain pavement markings and signs, while others only fix damaged devices when they are reported.

Availability of Data

One of the objectives of the interviews was to identify suitable locations for further analysis and request the associated cost and traffic data.

- Suitable locations. Due to the ongoing statewide rumble strip implementation effort, most districts interviewed during this project were able to identify recent projects where rumble strips were implemented. However, few districts were able to identify historical information on location and installation time for rumble strips that were installed multiple years ago. In addition, few districts maintain an inventory for other low-cost delineation treatments.

- Cost data. Most districts were able to identify cost information for rumble strips based on recent contracts. The data suggested that rumble strip installation costs vary significantly from project to project and from district to district. Few districts could provide information on the material and labor costs associated with other types of delineation devices.

- Traffic data. Districts typically rely on statewide AADT data for traffic/safety analysis and seldom conduct additional counts for analyses related to delineation treatments.

CMF Availability

In total, there were 1,120 CMFs relevant to these measures listed in the CMF Clearinghouse database when this review was conducted, of which 5.5% have a 5-star rating, 33% a 4-star rating, and 49% a 3-star rating. The information available for each CMF varies. As an example, more than half of the CMFs do not have a functional classification associated with them. Similarly, the number of lanes is not available in more than 25% of the CMFs identified.

An examination of the available CMFs by treatment categories showed that PMDs had the least CMFs available, followed by RPMs. Rumble strips, edgelines/centerlines, and safety edges on the other hand had the most CMFs among the treatment categories included in the scope of this project. In addition, the CMF availability for all treatment categories varied significantly by area type, roadway type and characteristics, and targeting crash type. In addition, many CMFs involved a combination of treatments, which therefore have very limited applicability for treatment scenarios other than the specific ones defined.

When looking at the CMF values for the studied delineation treatment categories, it became clear that the extremely limited CMFs for PMDs and RPMs varied significantly in value, with some exceeding 1 (indicating increased crashes after treatment). The majority of CMFs for other categories including chevron signs, centerlines/edgelines, centerline/shoulder rumble strips, and safety edges had a value below 1, indicating crash reductions after treatments. When considering their standard errors, however, many CMFs groups had maximum values well exceeding 1, indicating a large confidence interval.

In order to support the selection of CMFs when applying for Highway Safety Improvement Program projects, VDOT has developed a list of preferred CMFs. In the case of delineation treatments, CMFs were selected for freeway and non-freeway segments, by countermeasure and road functional classification (VDOT 2022). Table 9 and Table 10 list the basic conditions for the VDOT-preferred CMFs that are relevant to the treatments of this study. Readers are referred to the original source for the values and detailed information about the individual CMFs. As shown in the tables, some of the VDOT-selected CMFs use data collected in a single state.

The review of CMFs shows that they vary not just for type of crash and severity, but also for site characteristics, such as roadway type, area type, AADT, curve or tangent, radius, and number of crashes. Furthermore, it is not uncommon to see different CMFs for each state where the study was conducted. Selecting the best countermeasures to resolve a safety issue is not an easy task. Selecting the CMFs that allow VDOT engineers to evaluate different treatment alternatives therefore becomes important. Characteristics of the sites, possible treatments, and types of crashes to eliminate are all very important factors when selecting the best CMFs. The review of the relevant CMFs clearly showed that CMFs for the different influential factors are not necessarily included in the CMF Clearinghouse.

Table 9. VDOT-preferred CMFs for Non-freeways

Countermeasure	Data Site	Principal Arterial-Expressways	Other Principal Arterials	Two Lane	Rural	Crash Type
Shoulder rumble strips	MN, MO, PA	X			X	Run off road - right
Centerline rumble Strips	MN, PA, WA				X	Head on
RPM	LA	X				All
4 in to 6 in wide edgelines	KS			X	X	All
Upgrade to wet reflective PM (same value)	PDO – NC Injury (MN, NC, WA)	X				All
Upgrade PM by increasing retroreflectivity	NC					Night
Add chevron signs, curve warning, and sequential flashing beacons	Italy				X	Night
Add chevron sign horizontal curve	WA			X	X	Night
Dynamic speed feedback sign	AZ, FL, IA, OH, OR, TX, WA			X	X	All
Upgrade chevrons with fluorescent sheeting (curves)	CT				X	Night
Safety edge	FL, IA, NC, OH, PA		X	X	X	Run off road

Table 10. VDOT-preferred CMFs for Freeways

Countermeasure	Data Site	Interstates	Other Freeways/ Expressways	Rural	Crash Type
Add rumble stripes inside shoulder	NCHRP 17-45	X			Single vehicle
Add rumble stripes inside shoulder	NCHRP 17-45	X			Single vehicle
RPM	LA		X	X	All
Upgrade horizontal curve (= to upgrade chevron signs with fluorescent sheeting)	CT			X	All
Upgrade to wet reflective PM (same value)	PDO – NC Injury (MN, NC, WA)		X		All

Benefit-Cost Analysis Toolset

The benefit-cost analysis toolset for low-cost delineation measures was developed to allow VDOT district staff to select or prioritize low-cost delineation treatments based on the comparison analysis of treatment effectiveness and potential return on investment. To ensure the tool is readily available to VDOT users, the team developed it in Microsoft Excel, which is widely used in VDOT. In the toolset, cells for input data are clearly labeled and highlighted using different colors. The team purposely did not use cell protections and complex formulae so that users can modify the tools to better fit their needs. There are currently 10 tools (tabs or sheets) in the toolset (Figure 6). Each tool performs the analysis of BCRs for an individual type of low-cost delineation treatment.

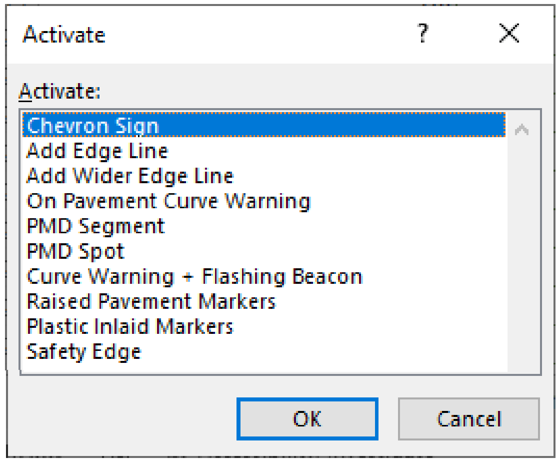


Figure 6. List of Tabs in Excel-based Benefit-Cost Analysis Toolset.

The tools can be generally divided into two groups: tools for spot treatments (i.e., at individual curve locations) and tools for systemic (i.e., large segment) applications. For systemic applications, the tools use VDOT SPFs to predict the expected number of crashes based on user input of AADT values on the facility. The prevented crashes are then determined using the expected crashes and the CMFs selected for the treatment. For spot treatments, users are required to enter the number of observed crashes, based on which the prevented crashes can be estimated using the CMFs. Note: the term "spot treatment" in this toolset refers to treatments applied to specific locations as compared to a systemic implementation regardless of curves or tangents. Such specific locations may be in the form of linear segments (e.g., a curved segment that may be referred to as a segment by the *Highway Safety Manual*). The following describe some important aspects of the tools included in the toolset:

- Segment/systemic treatments versus spot treatments. In the toolset, a spot treatment is defined as a treatment that is applied to a specific site (e.g., an individual curve, or a specific roadway section with known alignment and historical crash information). A segment treatment is defined as a treatment that is applied to a general roadway section without considering specific alignment details (e.g., an average 10-mile section of a two-lane rural highway with both curves and tangents). The SPFs used for segments reflect average safety experience for the subject facility type across the Commonwealth and are applied to a 10-mile roadway segment of the specified facility type.

- Calculation of BCRs. Each tool calculates a set of safety BCRs based on the treatment installation and maintenance costs and the benefits due to the estimated crash reductions for the associated delineation treatment. In addition to the BCRs calculated for the specified CMF, the tool also calculates two sets of BCRs based on the sensitivity analysis range entered by the user. The three sets of BCRs are then plotted on a chart, with the x-axis being AADT in the case of a segment treatment or number of crashes in the case of a spot treatment and the y-axis being BCR values.

- CMFs used for the tools. During this project, the team did not identify VDOT-preferred CMFs for any of the treatments included in the toolset. In addition, the CMF development effort of the project did not result in statistically significant CMFs due to the limited number of sites identified. Due to this reason, the project team used CMFs selected from the CMF Clearinghouse site for most treatments. Table 11 lists the CMFs used in the toolset.

Table 11. List of Crash Modification Factors Used in the Toolset

Tool	CMF Type	CMF	CMF ID
Chevron Sign	KABC	0.84	2438
	KABCO	0.96	2436
Add Edgeline	KABCO	0.848	10243
Add Wider Edgeline	KABC	0.635	4737
	KABCO	0.825	4736
On-Pavement Curve Warning	KABC	0.693	10313
	KABCO	0.616	9167
Post Mounted Delineator – Segment	KABC	0.9	9728
	KABCO	0.85	9727
Post Mounted Delineator – Spot	KABC	0.9	9728
	KABCO	0.85	9727
Curve Warning with Flashing Beacons*	-	-	-
Raised Pavement Markers	KABCO	0.87	5498
Plastic Inlaid Markers	KABCO	0.87	5498
Safety Edge	KABC	0.892	9660
	KABCO	0.989	9199

*The team did not identify suitable CMFs for this treatment. CMF = Crash modification factor, KABC = Fatal and injury crashes, and KABCO = Crashes of all severity levels.

- Input and parameter modification. There are four areas in the datasheet of each tool: the input area, the result table, the result chart, and the intermediate parameter and calculation area. The input fields are labeled by “Please select,” “Please fill,” or “Change if desired.” Any fields without such labels indicate default parameters or calculated results, which can be changed if the user is proficient and familiar with the calculations involved in the toolset.

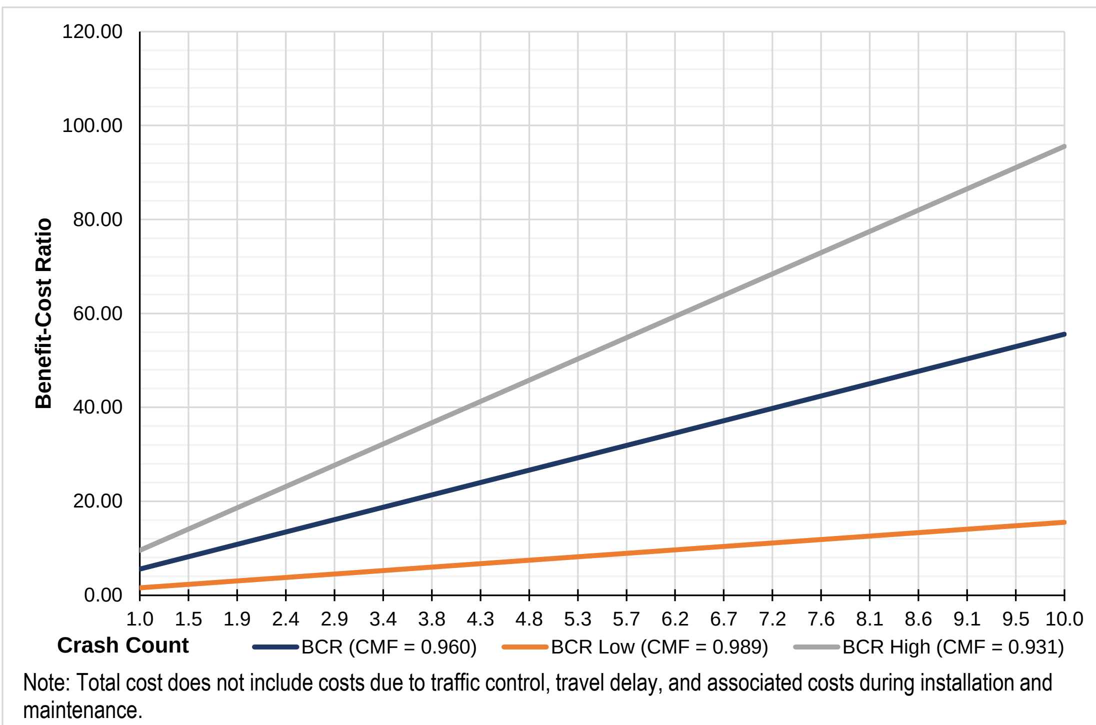
Chevron Sign

The chevron sign tool allows analysts to compare the BCRs of using chevron signs as a spot safety treatment at roadway curves with default or user-specified CMFs, potential crash range, and curve characteristics. The tool outputs a graph showing the potential BCR ranges with the given information for a specific application. Figure 7 shows the input section of the tool. Figure 8 shows an example graph of the BCR results for the chevron tool.

Analysis	Chevron Signs (Spot Treatment)
Base Year	2020
Discount Rate r (Change if desired)	7%
CMF Scenario (Please select)	KABCO
KABCO Unit Crash Cost	$108,065.86
Treatment Type (Please select)	Regular Chevron
Treatment Unit Cost (ft)	$420.50
Curve Length (ft) (Please fill)	1,000
Curve Radius (ft) (Please fill)	400
Chvron Spacing	80
Total Number of Units	13
Treatment Service Life	10
CMF	0.96
CMF Change for Sensitivity Analysis (Please	3.00%
Crash Count Range Lower (Please fill)	1
Crash Count Range Upper (Please fill)	10

CMF = Crash modification factor, KABCO = Crashes of all severity levels.

Figure 7. Input Section of Benefit-Cost Analysis Tool for Chevron Signs.



CMF = Crash modification factor, BCR = Benefit-cost ratio.

Figure 8. BCR Graph for Chevron Signs.

Add Edgelines

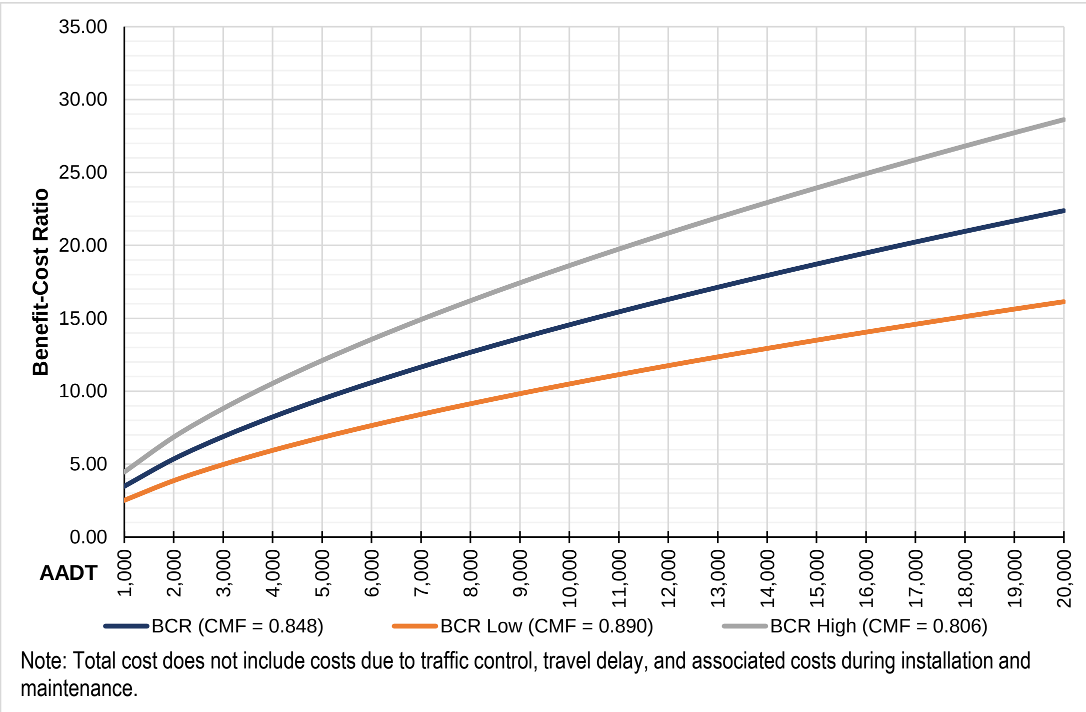
The Add Edgeline tool was designed for analysis of systemic (i.e., segment) application of edgelines as a safety treatment. The tool allows users to select a facility type for analysis and predicts the number of crashes based on the AADT range and edgeline type using a VDOT SPF.

BCRs are then calculated based on the predicted crashes and the selected CMF (Figure 9 and Figure 10).

Analysis	Add Edge Line
Base Year	2020
Discount Rate r (Change if desired)	7%
Facility Type (Please select)	Rural 2-lane segments
CMF Scenario (Please select)	KABCO
KABCO Unit Crash Cost	$108,065.86
Treatment Type (Please select)	Type A Pavement Line Marking 4"
Treatment Unit Cost (ft)	$0.12
Treatment Service Life	1
CMF	0.848
CMF Change for Sensitivity Analysis	5.00%
AADT Range Lower (Please fill)	1,000
AADT Range Upper (Please fill)	20,000

CMF = Crash modification factor, KABCO = Crashes of all severity levels, AADT = Average annual daily traffic.

Figure 9. Input Section of Benefit-Cost Analysis Tool for Add Edgelines.

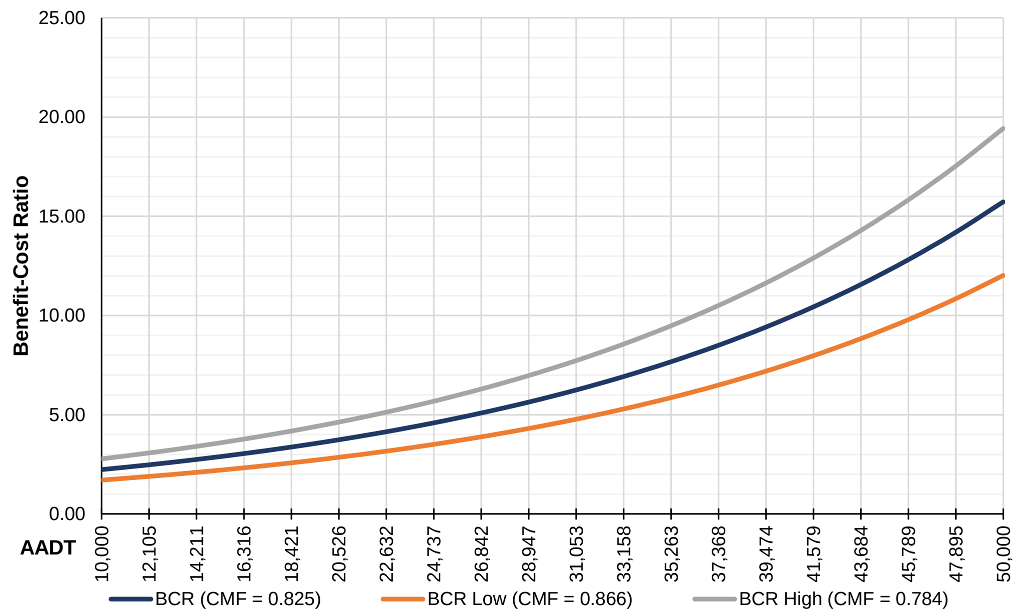


CMF = Crash modification factor, BCR = Benefit-cost ratio.

Figure 10. BCR Graph for Adding Edgelines.

Add Wider Edgelines

This tool is designed for users to analyze the BCRs for replacing regular edgelines with wider edgelines (i.e., 4-inch edgelines to 6-inch edgelines). Similarly, the tool requires users to specify the type of facilities analyzed, type of pavement marking materials used, and AADT of the roadway. Figure 11 shows an example output graph of BCRs for replacing regular edgelines with wider edgelines.



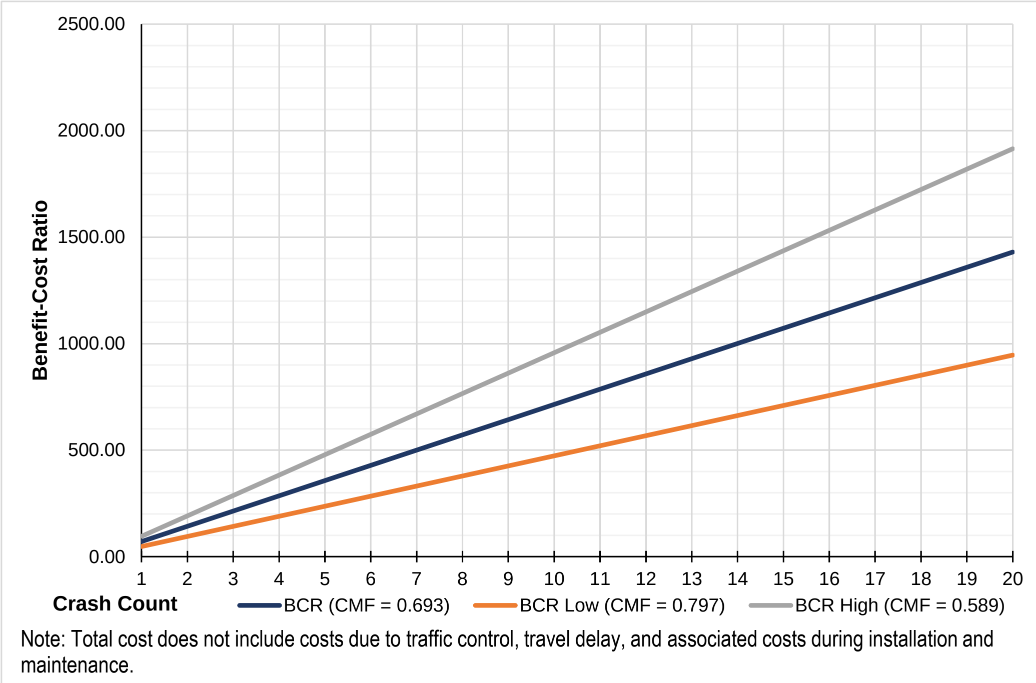
Note: Total cost does not include costs due to traffic control, travel delay, and associated costs during installation and maintenance.

CMF = Crash modification factor, BCR = Benefit-cost ratio.

Figure 11. BCR Graph for Adding Wider Edgelines.

On-Pavement Curve Warning

This tool is designed to analyze the BCRs for using on-pavement curve warning (a curve warning message marking) as a spot treatment to prevent crashes at roadway curves. Users are required to enter the potential number of crashes expected at the current sites. The tool then calculates ranges of BCRs when using this treatment at the sites specified. Figure 12 shows the output graph of BCRs from the tool.

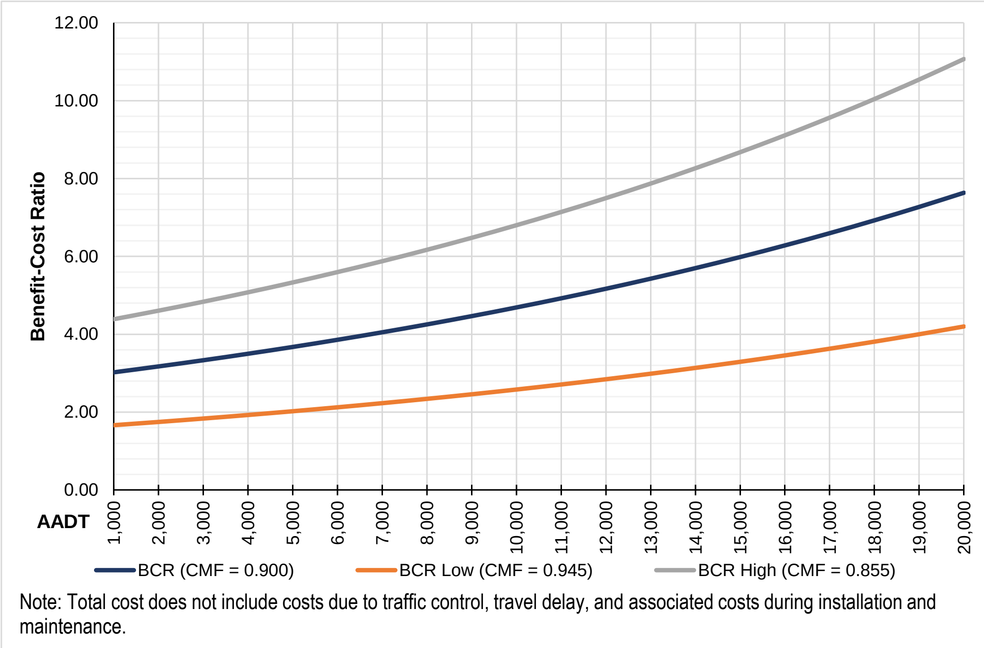


CMF = Crash modification factor, BCR = Benefit-cost ratio.

Figure 12. BCR Graph for On-pavement Curve Warning.

PMD for Segment

This tool analyzes the BCRs for PMDs when used as a safety treatment for roadway segments. The tool requires users to specify the type of facility analyzed and the AADT range for the facility. Similar to all other tools, it then calculates BCRs, including a sensitivity analysis based on the user-specified sensitivity range for the selected CMF. Figure 13 is an example graphic output showing the BCRs calculated for PMDs used on highway segments as a delineation treatment.

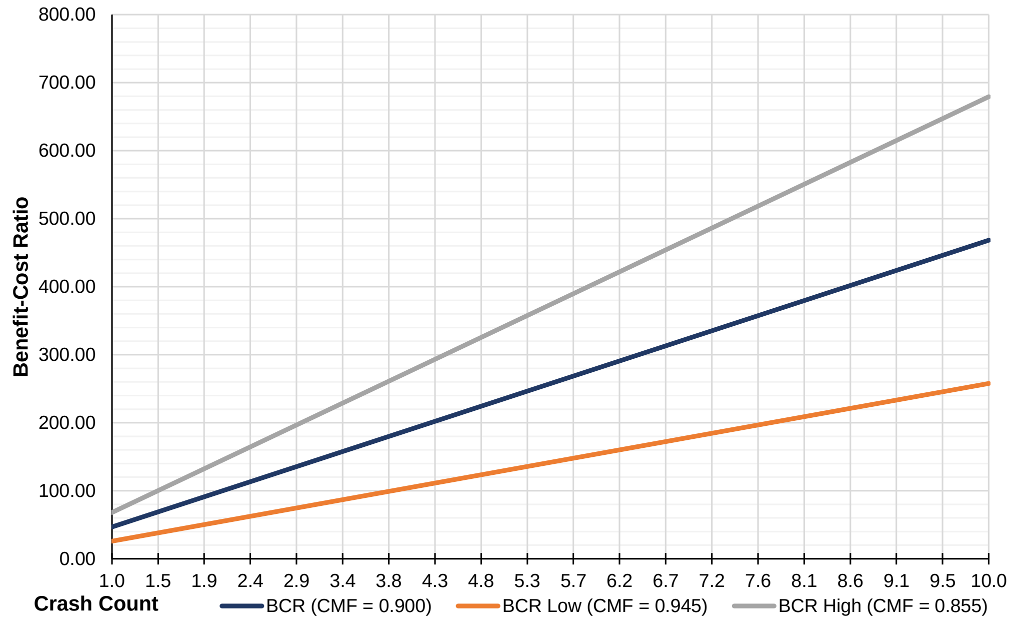


CMF = Crash modification factor, BCR = Benefit-cost ratio.

Figure 13. BCR Graph for PMDs (Segment Application).

PMD for Spot Treatment

This tool analyzes the BCRs for using PMDs at roadway curves as a spot treatment to prevent RDCs. The user enters curve information and observed crashes, and the tool outputs the BCRs based on the input information. Figure 14 shows sample graphic output of the BCR analysis results.

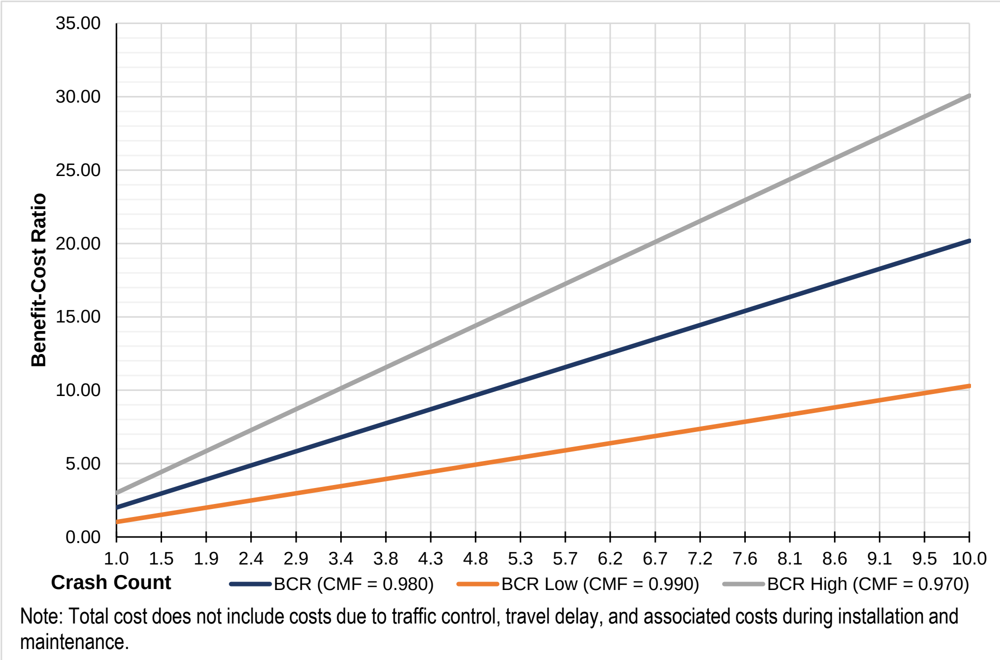


Note: Total cost does not include costs due to traffic control, travel delay, and associated costs during installation and maintenance.

Figure 14. BCR Graph for PMDs (Spot Application).

Curve Warning with Flashing Beacons

This tool analyzes the potential BCR scenarios based on the crash information input for using CWS with flashing beacons at roadway curve locations. Figure 15 shows an example output for BCRs calculated for CWS with flashing beacons.

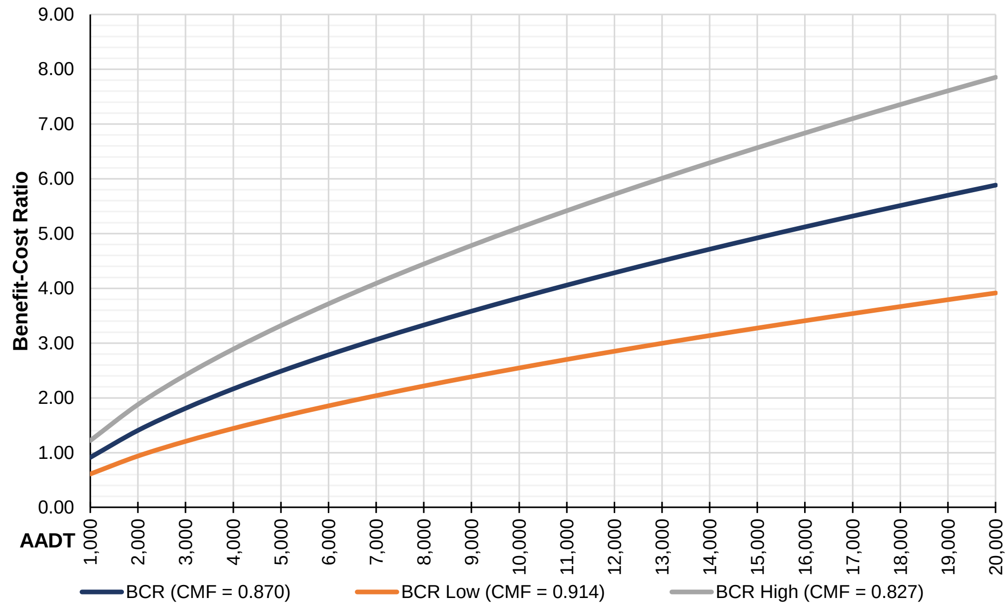


CMF = Crash modification factor, BCR = Benefit-cost ratio.

Figure 15. BCR Graph for CWS with Flashing Beacons.

Raised Pavement Markers

This tool allows users to estimate the BCRs for using RPMs as a delineation treatment for roadway segments. The tool requires that users input the number of RPMs, the type of facilities analyzed, and the AADT range for the facilities analyzed. Figure 16 shows an example of the graphic output of the tool.



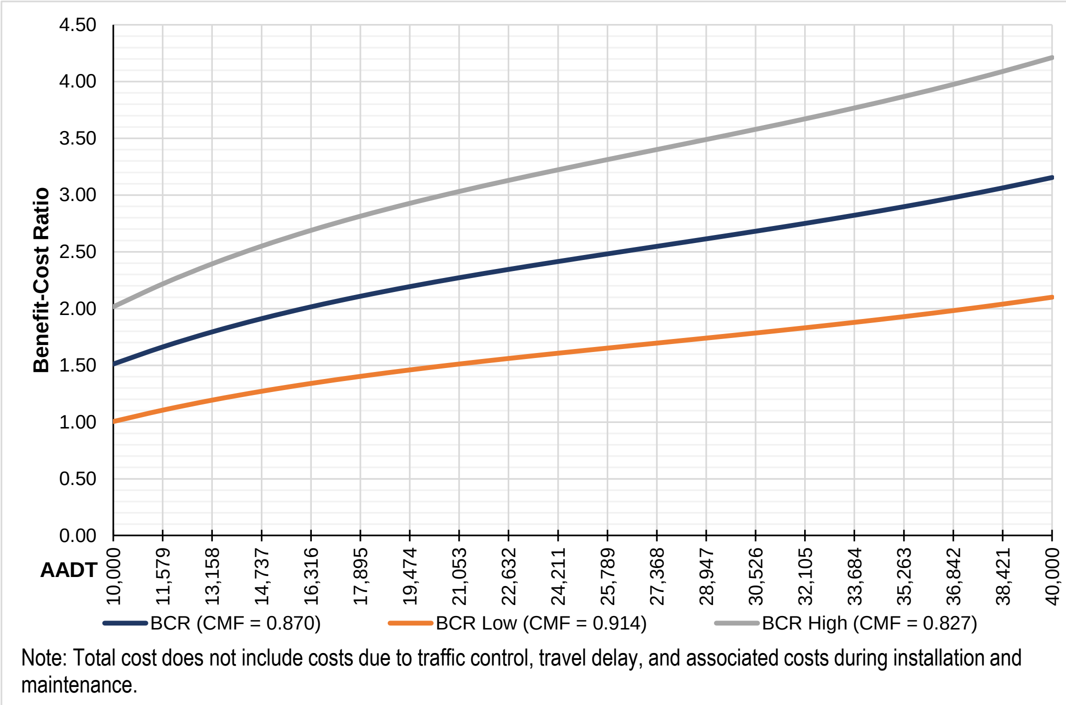
Note: Total cost does not include costs due to traffic control, travel delay, and associated costs during installation and maintenance.

CMF = Crash modification factor, BCR = Benefit-cost ratio.

Figure 16. BCR Graph for RPMs.

Plastic Inlaid Markers

This tool allows users to assess the BCRs for using PIMs as a delineation treatment on roadway segments to prevent RDCs. When using the tool, users need to specify the types of facilities to be analyzed, the number of PIMs to be installed, and the AADT ranges to be analyzed. Figure 17 is a sample graphic output from the tool showing the BCR ranges.

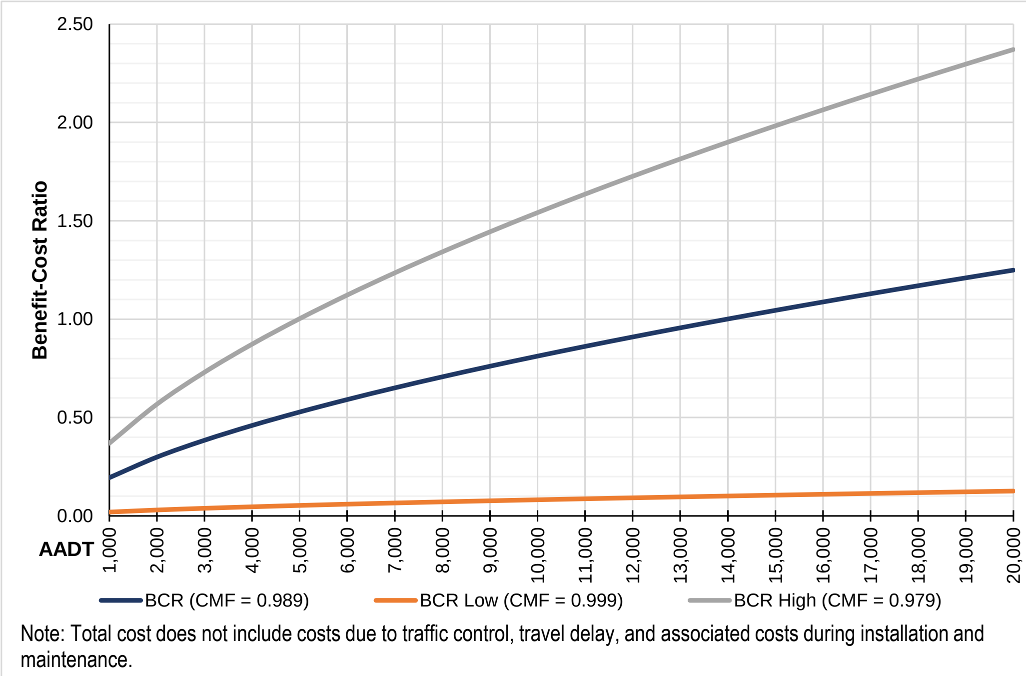


CMF = Crash modification factor, BCR = Benefit-cost ratio.

Figure 17. BCR Graph for PIMs.

Safety Edge

The BCR tool for Safety Edge is designed to evaluate the BCRs when considering Safety Edge as a safety treatment for roadway segments. The tool requires users to input the facility type and AADT range in order to assess the BCRs. Figure 18 shows an example of the BCR output from the tool.



CMF = Crash modification factor, BCR = Benefit-cost ratio.

Figure 18. BCR Graph for Safety Edge.

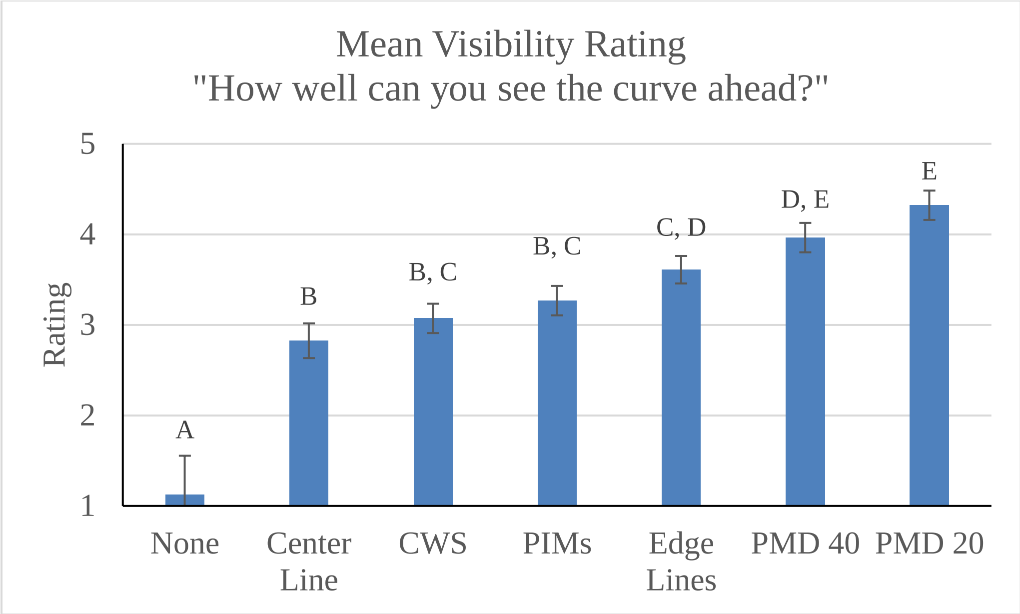
Human Factors Results

The data resulting from the human factors study included a participant survey, a point-based dataset, and a full-curve data set. Each set of results is described below.

Survey Results

Effect of Treatments on Curve Visibility

Participants were asked to rate how visible a curve was on a scale from 1 to 5, where 1 meant the curve was not visible at all, and 5 meant the curve was clearly visible. The effect of treatment on visibility rating was examined, and statistically significant differences were found among the different treatment types. Figure 19 shows the mean visibility rating for each treatment with standard error bars. The letters above each bar represent results of the pairwise comparisons; pairs that do not share a letter are statistically significantly different. As an example, the ratings for centerlines and edgelines are significantly different from each other, but the ratings of CWS and PIMs are not. The visibility rating for the 20-foot PMDs was significantly higher than all other treatments, except the 40-foot PMDs. There was no statistical difference among CWS, edgelines, or PIMs. The visibility rating for curves with just a centerline was not significantly different from curves with a CWS or PIMs but was significantly lower than curves with edgelines.

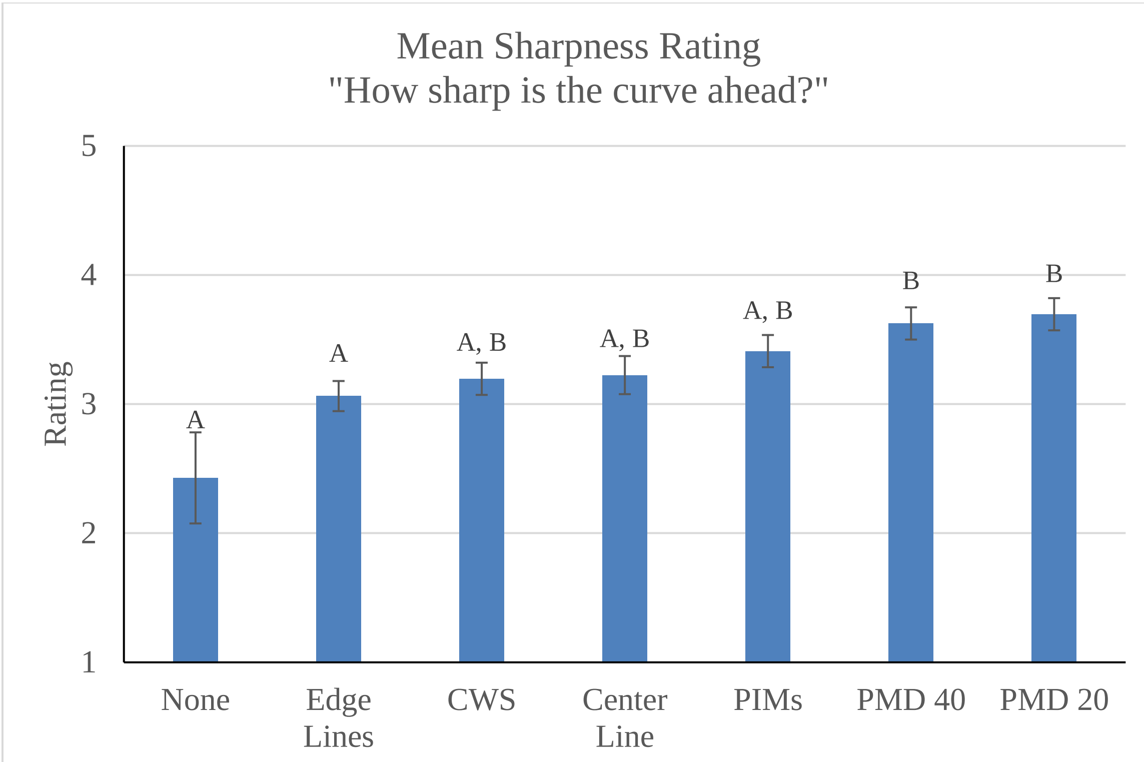


CWS = Curve Warning Sign, PIMs = Plastic Inlaid Markers, PMD 40 = Post-mounted Delineators with 40-ft spacing, and PMD 20 = Post-mounted Delineators with 20-ft spacing.

Figure 19. Mean Visibility Rating by Treatment. Note that the letters above each bar represent results of the pairwise comparisons; pairs that do not share a letter are statistically significantly different.

Treatment Effectiveness on Perceived Curve Sharpness

Participants were asked to rate how sharp a curve appeared on a scale from 1 to 5, where 1 meant it was “not sharp” and 5 meant it was “very sharp.” Figure 20 shows the mean sharpness rating with standard error bars. Curves with PMDs were rated significantly sharper than curves with edgelines and curves with no treatment but were not statistically different from each of the other treatments.

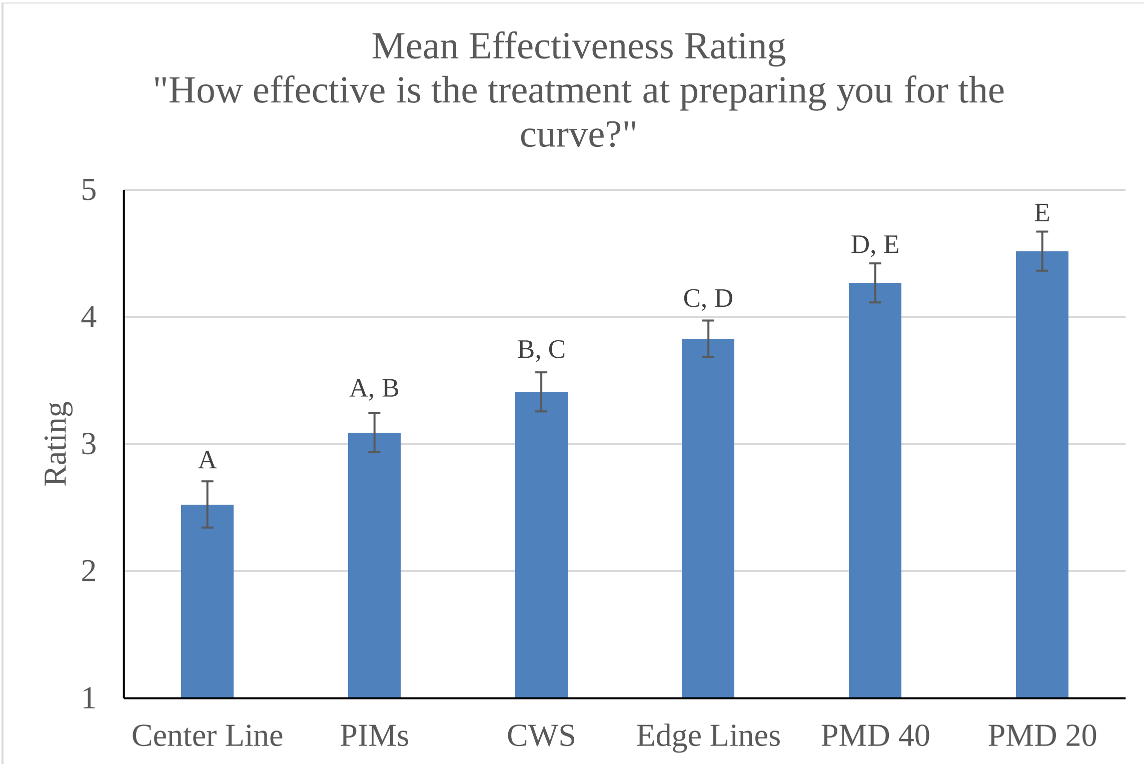


CWS = Curve Warning Sign, PIMs = Plastic Inlaid Markers, PMD 40 = Post-mounted Delineators with 40-ft spacing, and PMD 20 = Post-mounted Delineators with 20-ft spacing.

Figure 20. Sharpness Rating by Treatment. Note that the letters above each bar represent results of the pairwise comparisons; pairs that do not share a letter are statistically significantly different.

Perceived Treatment Effectiveness

Participants were asked to rate the effectiveness of each treatment with regard to how well it prepared them for the curve on a scale from 1 to 5, where 1 meant it was “not effective” and 5 meant it was “very effective.” Figure 21 shows the mean effectiveness rating for each treatment. The 20-foot PMDs were rated significantly more effective than all other treatments except for the 40-foot PMDs. Centerlines had the only below average rating (less than 3) and were rated significantly less effective than all other treatments except for the PIMs. Note that 6 of the 7 curves have centerlines as part of the baseline (see Table 6).

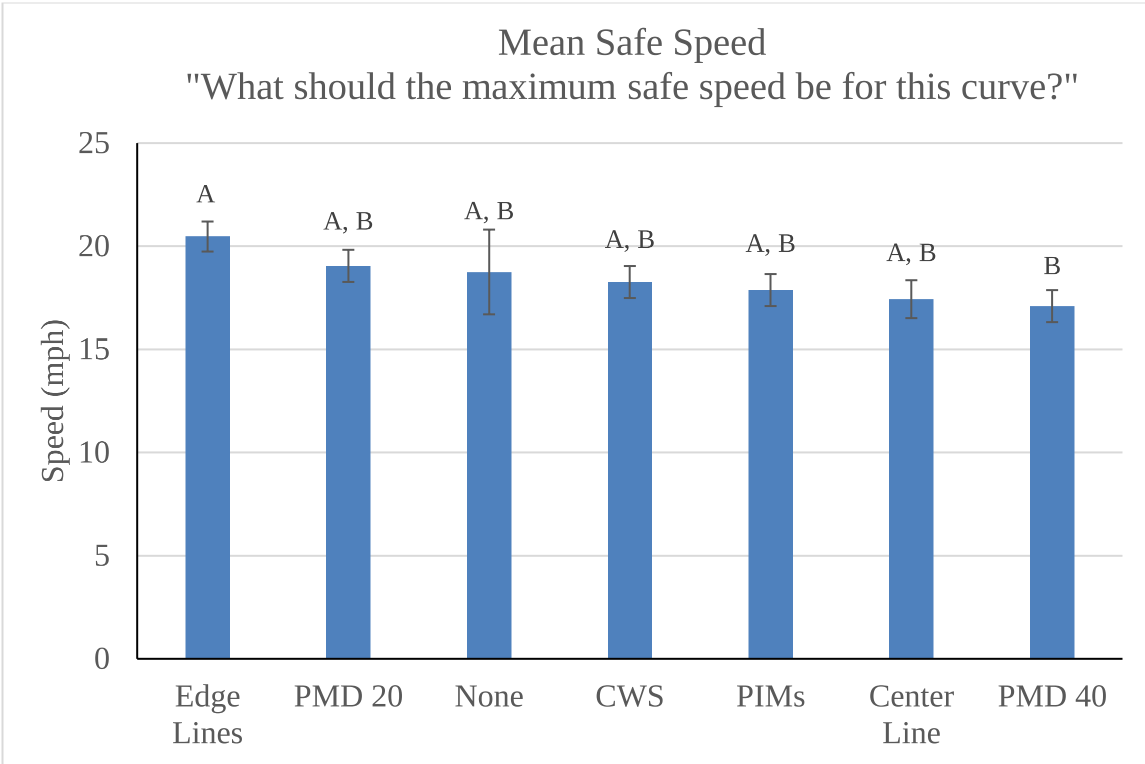


CWS = Curve Warning Sign, PIMs = Plastic Inlaid Markers, PMD 40 = Post-mounted Delineators with 40-ft spacing, and PMD 20 = Post-mounted Delineators with 20-ft spacing.

Figure 21. Effectiveness Rating by Treatment. Note that the letters above each bar represent results of the pairwise comparisons; pairs that do not share a letter are statistically significantly different.

Treatment Effects on Perceived Maximum Safe Speed

Participants were asked to specify what they believed the maximum safe speed should be for each curve. Figure 22 shows the mean speed by treatment based on participant perceptions. The treatment had little effect on participants' perceptions of what a maximum safe speed should be. The means for all treatments fell between 17 and 20 mph, including when there was no treatment at all. The only significant difference was found between edgelines (20.5 mph) and the 40-foot PMDs (17.1 mph).

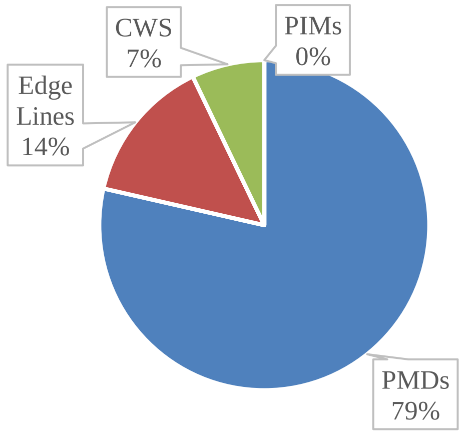


CWS = Curve Warning Sign, PIMs = Plastic Inlaid Markers, PMD 40 = Post-mounted Delineators with 40-ft spacing, and PMD 20 = Post-mounted Delineators with 20-ft spacing.

Figure 22. Mean Safe Speed by Treatment. Note that the letters above each bar represent results of the pairwise comparisons; pairs that do not share a letter are statistically significantly different.

Most Effective Treatment

Once participants had finished rating each curve, they were asked to select which treatment they thought was the most effective among the four types used in this study (CWS, edgelines, PIMs, and PMDs). For this question, no distinction was made between 20-foot and 40-foot PMDs. Figure 23 shows the total number of times each treatment was selected as the most effective. Participants overwhelmingly selected the PMDs as the most effective treatment. No participants selected the PIMs as the most effective treatment.

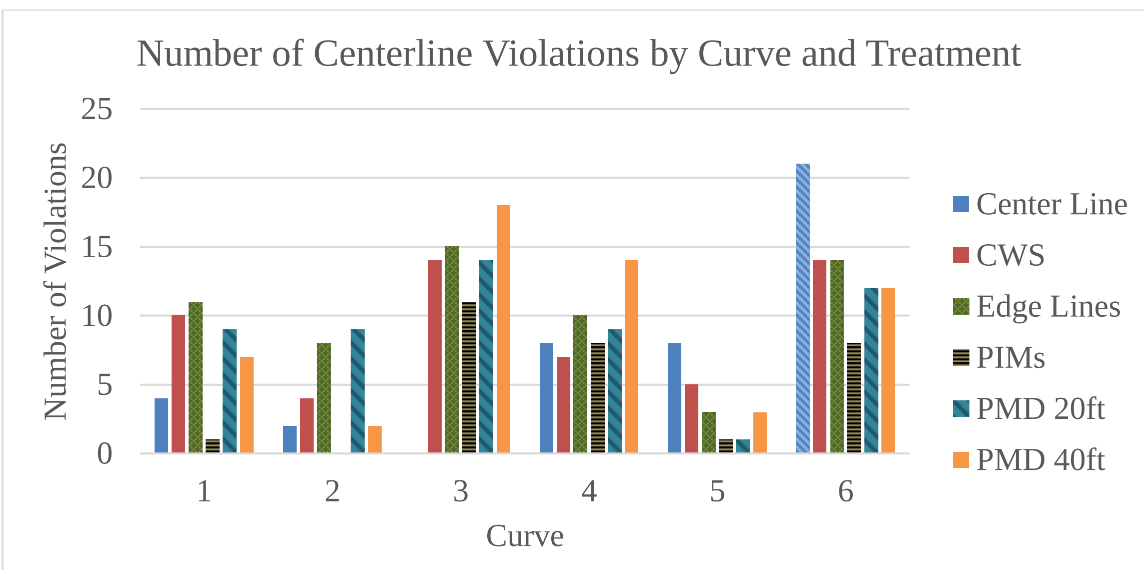


CWS = Curve Warning Sign, PIMs = Plastic Inlaid Markers, PMDs = Post-mounted Delineators.

Figure 23. Percentage of Participants Considering Treatment as the Most Effective.

Lane Violation Data Analysis Results

The number of times that participants crossed the centerline in a curve was counted. Figure 24 shows the number of centerline violations by curve and treatment. Curve 7 was not included because it had no centerline. Curves 3 and 6 had a higher number of lane violations because they were the two smallest radius curves. For Curve 6, the addition of any treatment appeared to reduce the number of lane violations when compared to the baseline "Centerline" condition. In general, centerline lane violations were reduced when PIMs were used along the centerline.



CWS = Curve Warning Sign, PIMs = Plastic Inlaid Markers, PMD 40 = Post-mounted Delineators with 40-ft spacing, and PMD 20 = Post-mounted Delineators with 20-ft spacing.

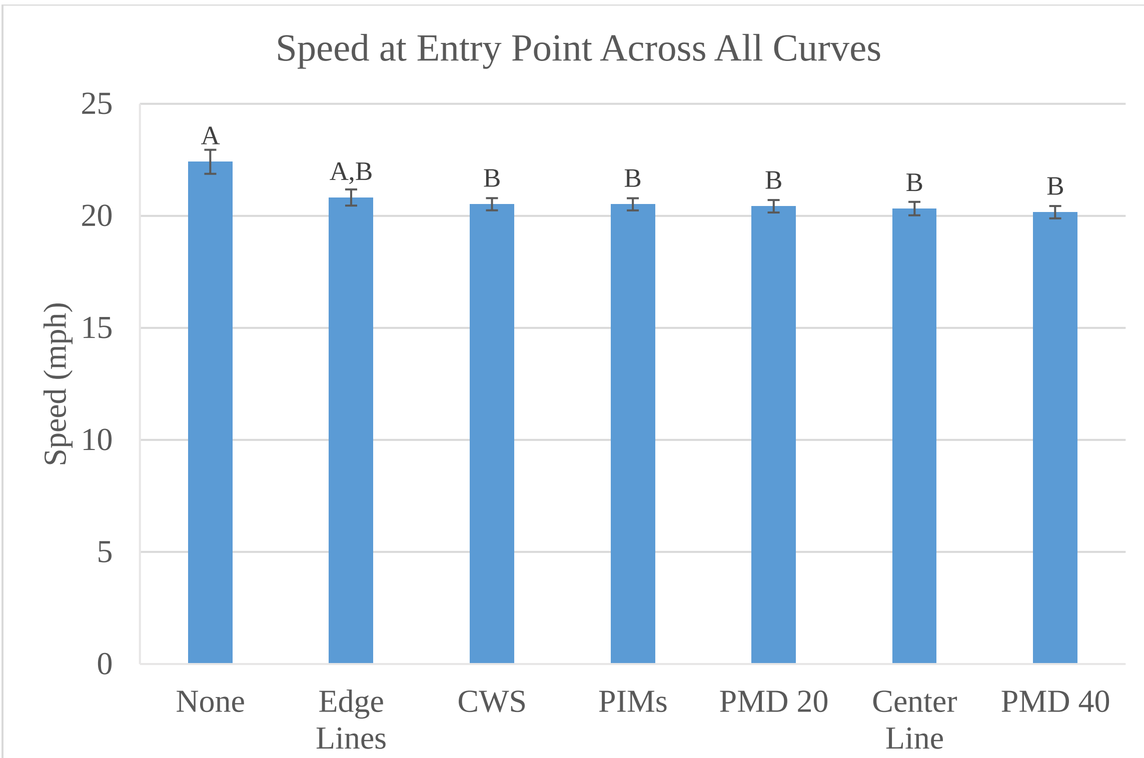
Figure 24. Centerline Violations by Curve and Treatment.

Driver Behavior Data Analysis Results Based on Point Data

This section only discusses the statistically significant results based on the linear mixed-effect modeling.

Entry Speed

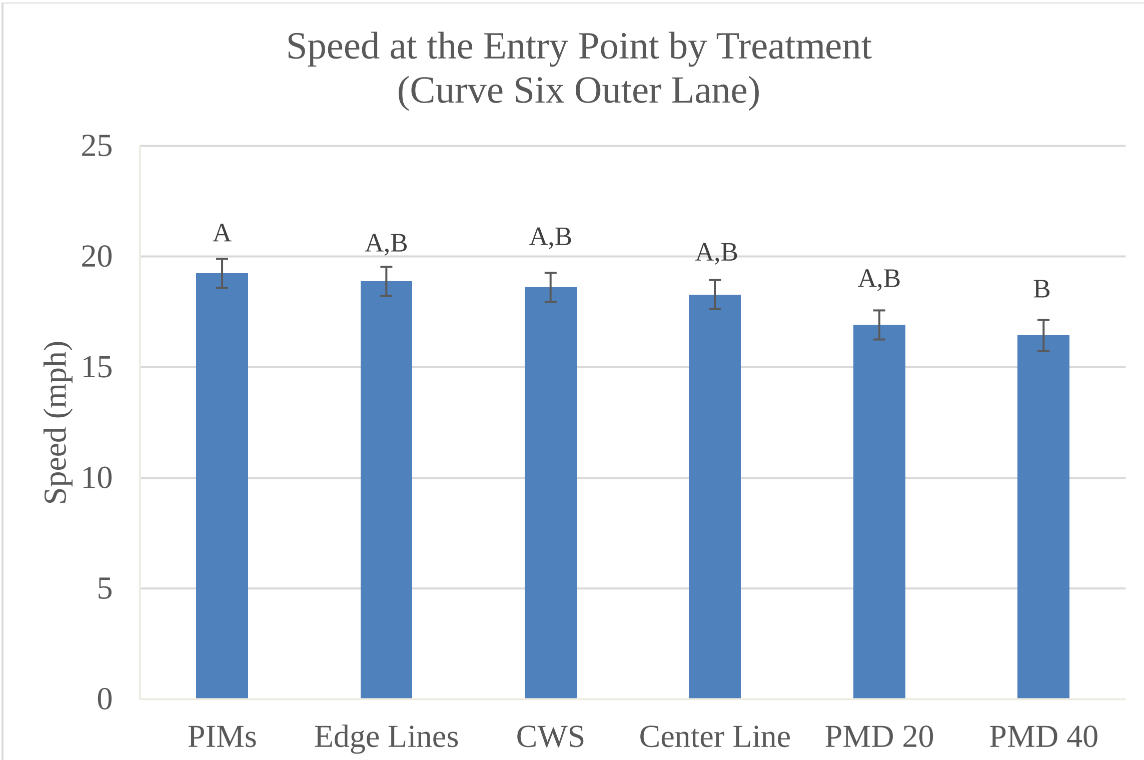
The effect of treatment on participants' speed at the curve entry point (i.e., entry speed) was examined. Figure 25 shows the mean speed at the entry point for each treatment. This analysis involved all curves and all travel directions. In general, the PMD 40 treatment had the lowest (not statistically significant in most cases) average entry speed compared to all other treatment scenarios. The ANOVA test showed that the entry speed was significantly (with a *p*-value of 0.004) higher for the "None" condition compared to all other treatments except for edgelines. Note that the "None" condition only reflected data for the baseline condition for Curve 7. No statistically significant difference was found among any of the treatments.



CWS = Curve Warning Sign, PIMs = Plastic Inlaid Markers, PMD 40 = Post-mounted Delineators with 40-ft spacing, and PMD 20 = Post-mounted Delineators with 20-ft spacing.

Figure 25. Mean Speed at Entry Point for All Data. Note that the letters above each bar represent results of the pairwise comparisons; pairs that do not share a letter are statistically significantly different.

When comparing the entry speeds by individual curve for the different treatment scenarios, a significant (with a *p*-value of 0.029) effect of treatment was found for the outer lane direction of Curve 6. As shown in Figure 26, the PMD 40 treatment corresponded with the lowest entry speed on the curve, following the same trend of the overall data. For the outer lane of Curve 6, which included a downhill slope, participants had a significantly higher mean entry speed with the PIMs (19.2 mph) than with the 40-foot PMDs (16.4 mph). The height of the PMDs above the road surface may have made them more visible than other treatments on the downhill slope (Note that the other treatments are on the roadway surface or are not highlighting the curve radius as the PMDs do).



CWS = Curve Warning Sign, PIMs = Plastic Inlaid Markers, PMD 40 = Post-mounted Delineators with 40-ft spacing, and PMD 20 = Post-mounted Delineators with 20-ft spacing.

Figure 26. Speed at Entry Point for Curve 6 Outer Lane. Note that the letters above each bar represent results of the pairwise comparisons; pairs that do not share a letter are statistically significantly different.

When analyzing the entry speed data by curve length group and treatment in the same model, the multivariate mixed-effect linear model (Table 12) showed that curve length as a categorical variable was significantly correlated with entry speeds. The treatment variable in the multivariate model becomes not significant. In addition, the interaction of treatment and length combination was non-significant as well. The modeling results suggested that the entry speed was significantly higher for “Longer” curves (22.4 mph) than “Medium” curves (20.9 mph), which was significantly higher than “Shorter” curves (19.6 mph). As explained in Table 4 and Figure 1, longer curves included Curves 2 and 7, while shorter curves referred to Curves 1, 3, and 6.

Table 12. ANOVA Results for Speed Entry by Treatment and Curve Length

Type 3 Tests of Fixed Effects				
Effect	**Num DF**	**Den DF**	**F Value**	**Pr > F**
Treatment	5	384	1.64	0.1489
Length	2	941	90.76	<.0001
Treatment*Length	10	1068	1.26	0.2461

The interaction between Treatment and Curve Radius was similarly examined in a multivariate linear mixed-effect model. As with Curve Length, the main effect of Radius was significant, but the interaction with Treatment was not (Table 13). Entry speed at "Larger" radius curves (22.4 mph) and at "Medium" radius curves (22 mph) was significantly higher than at "Smaller" radius curves (19 mph), but the speeds were not significantly different from each other. Similarly, in Table 4 and Figure 1, Curves 3, 4, and 6 were considered to have relatively smaller radii, while Curves 5 and 7 were in the group of curves considered to have relatively larger radii.

Table 13. ANOVA Results for Speed Entry by Treatment and Curve Radius

Type 3 Tests of Fixed Effects				
Effect	**Num DF**	**Den DF**	**F Value**	**Pr > F**
Treatment	5	363	1.94	0.087
Radius	2	877	250.07	<.0001
Treatment*Radius	10	995	1.25	0.2567

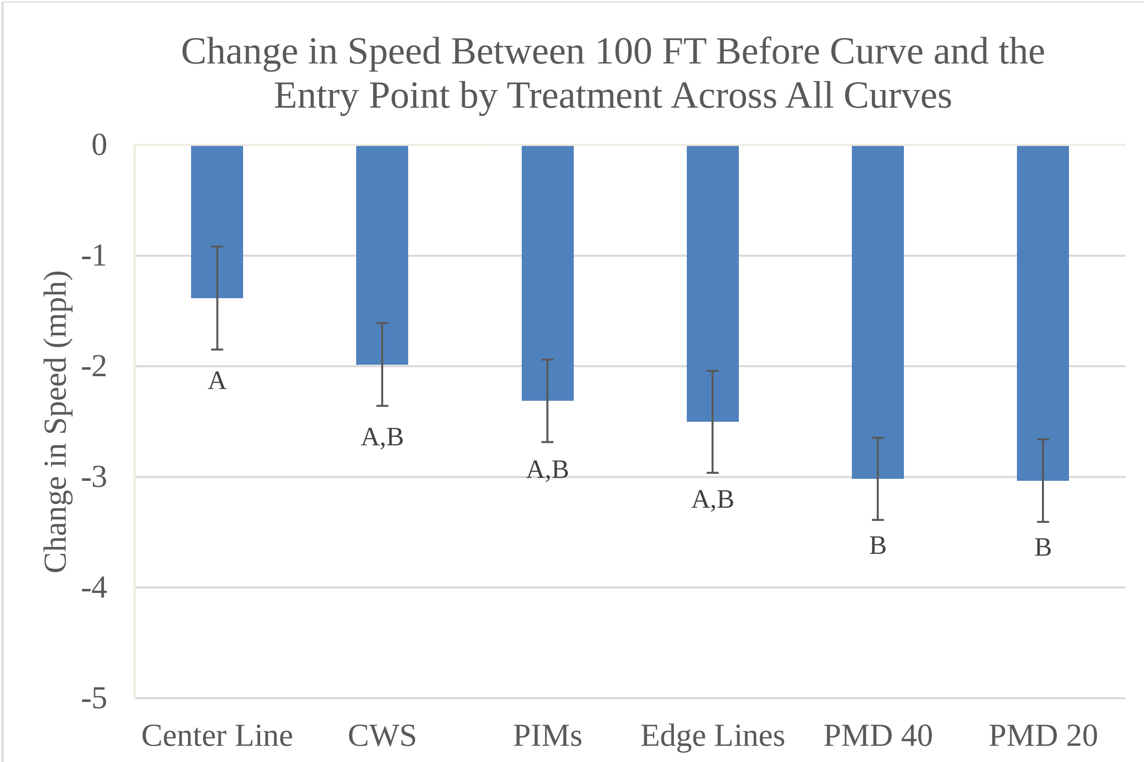
These results correlated with previous studies that showed that while curve speed is influenced by several factors, radius of curvature may be the most important one. In addition, speed pattern has shown to be particularly dependent on radius of curvature for curves with a radius of less than 820 feet, as they are the majority of the curves in this study (Campbell et al. 2012).

Reduction in Speed from Tangent to Entry

The effect of treatment on the change in speed from the tangent to the entry point was examined to determine if any treatments encouraged participants to slow down prior to entering the curve. Each time a participant drove through a curve, the difference in their speed 100 feet before the curve and their speed at the curve entry point was calculated. The analysis of this specific section only included curves in which participants had enough space to gain speed prior to a curve. So that each curve was equally represented, only one lane from each curve was included. As a result, the analysis only included the inner curve direction for Curves 1, 2, 3, 6, and 7 and the outer curve direction for Curve 4. Table 14 lists the mean speed at 100 feet before each curve entry point. The shaded cells are the curve-direction combinations analyzed in this analysis. These curve-direction combinations contained a tangent at least 100 feet long followed by a study curve. A significant effect of treatment was found for the change in speed ($p = 0.0126$). Figure 27 shows the change in speed for each treatment. The PMDs resulted in significantly greater change in speed than the centerlines. On average, participants reduced their speed by about 3 mph when the PMDs were present.

Table 14 Mean Speed (mph) at 100 ft Before Curve Entry

Curve No.	1	2	3	4	5	6	7
Inner Lane	22.22	24	27.81	22.05	16.59	23.3	25.04
Outer Lane			20.38	25.15	19.12	19.28	20.28



CWS = Curve Warning Sign, PIMs = Plastic Inlaid Markers, PMD 40 = Post-mounted Delineators with 40-ft spacing, and PMD 20 = Post-mounted Delineators with 20-ft spacing.

Figure 27. Change in Speed from Tangent to Curve Entry by Treatment. Note that the letters above each bar represent results of the pairwise comparisons; pairs that do not share a letter are statistically significantly different.

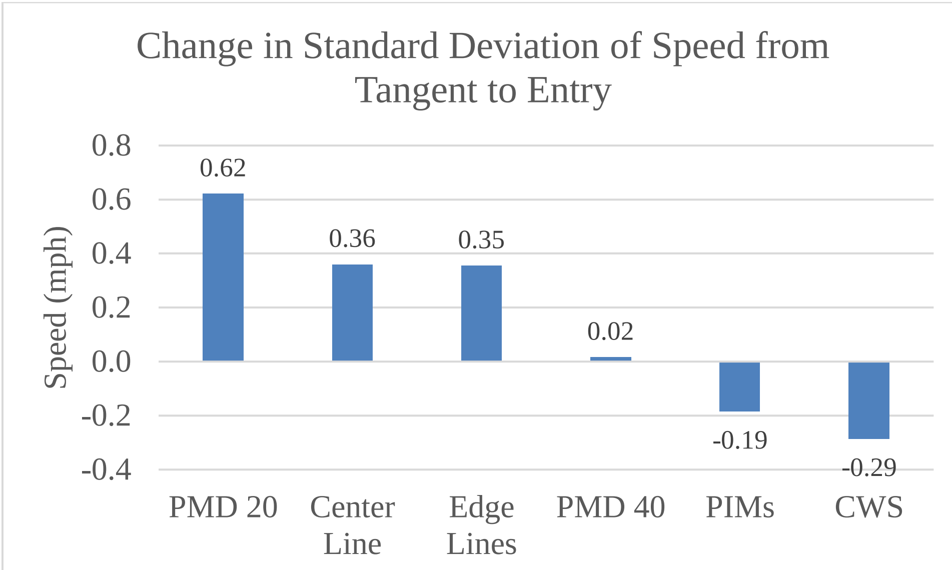
Change in Speed Variability from Tangent to Entry

The change in speed variability was also examined using the same data. For each treatment, the standard deviation of speed at the entry point was subtracted from the standard deviation of speed 100 feet before the curve to see if any treatment encouraged a narrowing of speed variability (Table 15).

Table 15. Standard Deviation of Speed by Treatment

Standard Deviation of Speed (mph)			
Treatment	**100 ft**	**Entry**	**Change**
CWS	2.73	2.45	-0.29
PIM	3.23	3.04	-0.19
PMD – 40 ft	3.08	3.10	0.02
Edgelines	2.84	3.20	0.35
Centerline	2.58	2.94	0.36
PMD – 20 ft	2.54	3.16	0.62

This change is illustrated in Figure 28. For the baseline “Centerline” condition, there was an increase in speed variability from the tangent to the entry. Compared to the baseline condition, there was a further increase in speed variability for the 20-foot PMDs, the centerlines and the edgelines, and no change for the PMD 40, and a decrease in variability for other treatments. The PIMs and CWS were the only conditions in which speed variability was smaller at the entry point than in the tangent.

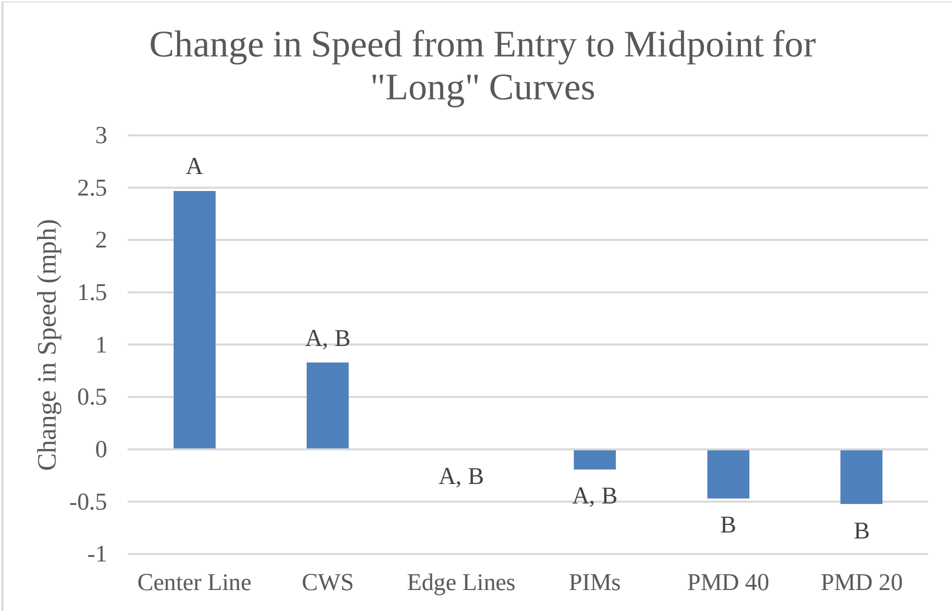


CWS = Curve Warning Sign, PIMs = Plastic Inlaid Markers, PMD 40 = Post Mounted Delineators with 40-ft spacing, and PMD 20 = Post Mounted Delineators with 20-ft spacing.

Figure 28. Change in Standard Deviation of Speed from Tangent to Entry.

Change in Speed from Entry to Midpoint

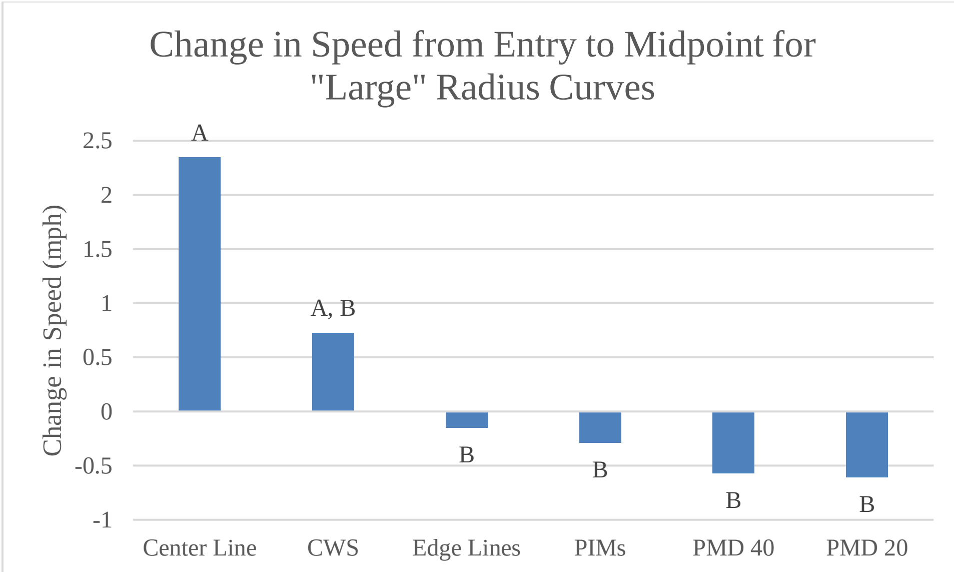
The effect of treatment on the change in speed from the curve entry point to the curve midpoint was also examined. No significant main effect of treatment was found. Significant interactions for treatment and length, as well as treatment and radius, were found. Figure 29 illustrates the significant effect of treatment for "Longer" curves. On "Longer" curves with PMDs, participants' change in speed from the entry to midpoint was significantly lower than the baseline "Centerline." On average, participants' speed increased by nearly 2.5 mph when only a centerline was present, while it decreased by approximately 0.5 mph with the addition of the PMDs.



CWS = Curve Warning Sign, PIMs = Plastic Inlaid Markers, PMD 40 = Post-mounted Delineators with 40-ft spacing, and PMD 20 = Post-mounted Delineators with 20-ft spacing.

Figure 29. Change in Speed from Entry to Midpoint for "Long" Curves. Note that the letters above each bar represent results of the pairwise comparisons; pairs that do not share a letter are statistically significantly different.

A similar significant effect was found for treatment on "larger" radius curves (Figure 30). On average, participants' speed increased by about 2.3 mph from the entry to the midpoint on "larger" radius curves with just a centerline. For each other treatment (except the CWS), participants' speed decreased. The PMDs had the largest decrease of approximately 0.6 mph.



CWS = Curve Warning Sign, PIMs = Plastic Inlaid Markers, PMD 40 = Post-mounted Delineators with 40-ft spacing, and PMD 20 = Post-mounted Delineators with 20-ft spacing.

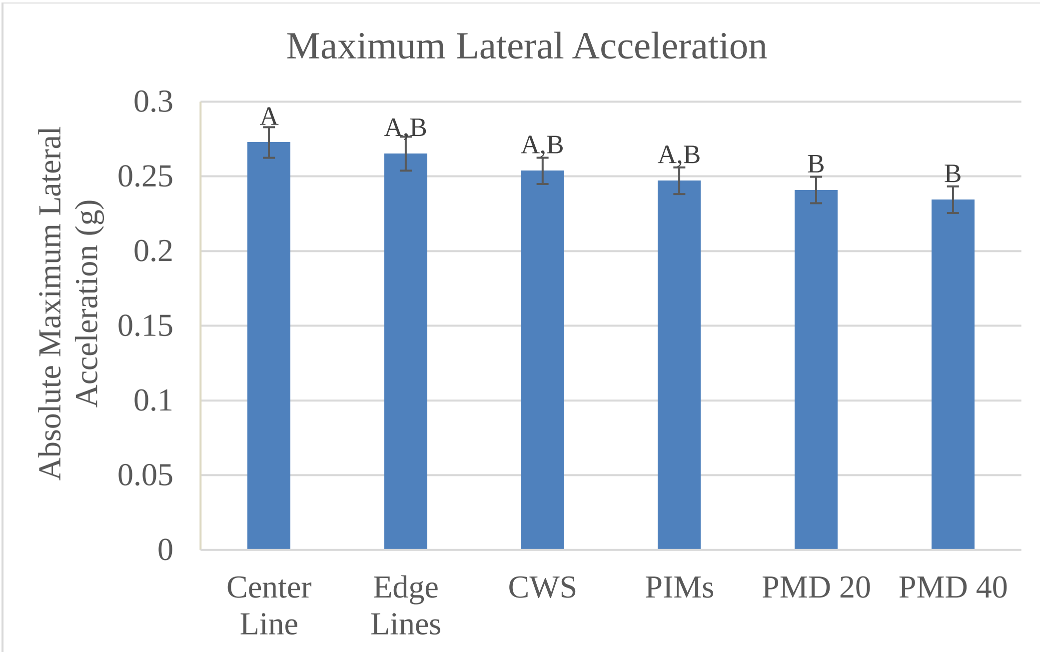
Figure 30. Change in Speed from Entry to Midpoint for "Large" Radius Curves. Note that the letters above each bar represent results of the pairwise comparisons; pairs that do not share a letter are statistically significantly different.

Driver Behavior Data Analysis Results Based on Full-curve Data

This section includes statistically significant findings of the curve-level data analyses.

Maximum Lateral Acceleration

The effect of treatment on lateral acceleration was examined based on the data only for curves with a leading tangent (i.e., inner curve direction for Curves 1, 2, 3, 6, and 7 and the outer curve direction for Curve 4 as listed in Table 4 but ignoring the "None" condition from Curve 7). The DAS recorded lateral acceleration as a positive value when turning to the right and negative when turning to the left. In this analysis, the absolute value of the lateral acceleration was used and the maximum value (i.e., the highest lateral g-force) was determined for each lap that participants drove through a curve. A significant effect was found in which the maximum lateral acceleration for centerlines was significantly higher than that of the 40-foot PMDs (Figure 31). Interactions with curve length and radius were not significant.

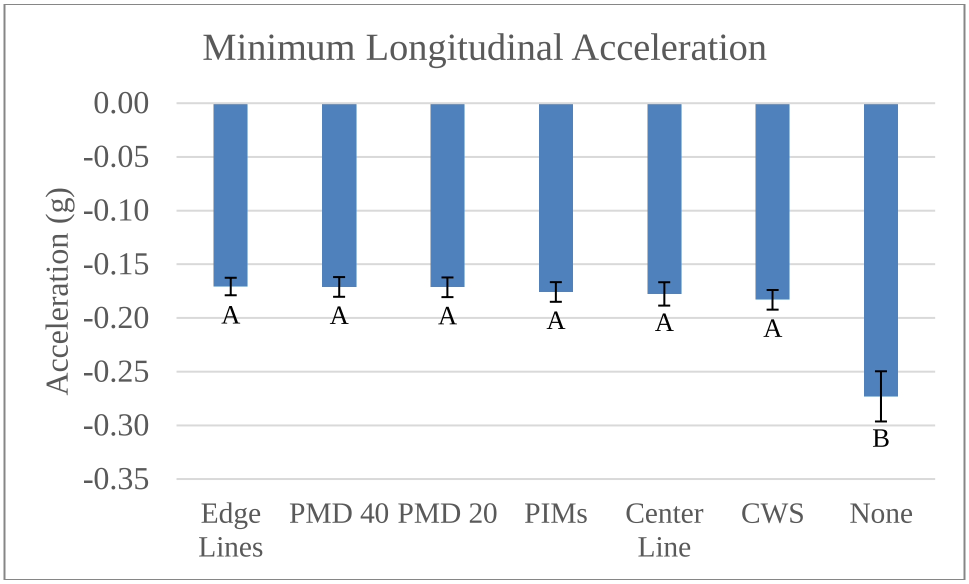


CWS = Curve Warning Sign, PIMs = Plastic Inlaid Markers, PMD 40 = Post-mounted Delineators with 40-ft spacing, and PMD 20 = Post-mounted Delineators with 20-ft spacing.

Figure 31. Maximum Lateral Acceleration by Treatment. Note that the letters above each bar represent results of the pairwise comparisons; pairs that do not share a letter are statistically significantly different.

Maximum Negative Longitudinal Acceleration

The effect of treatment on maximum negative longitudinal acceleration was examined. This represented the hardest deceleration that occurred each time a participant traversed a curve. The effect of treatment was significant (p = 0.005). Figure 32, however, shows that only the "None" condition on Curve 7 had a significantly lower minimum longitudinal acceleration than each of the other treatments. There was no difference among treatments.



CWS = Curve Warning Sign, PIMs = Plastic Inlaid Markers, PMD 40 = Post-mounted Delineators with 40-ft spacing, and PMD 20 = Post-mounted Delineators with 20-ft spacing.

Figure 32. Minimum Longitudinal Acceleration by Treatment. Note that the letters above each bar represent results of the pairwise comparisons; pairs that do not share a letter are statistically significantly different.

Summary of Human Factors Study

The human factors study showed:

- There was a strong subjective preference for the PMDs among participants. The PMDs were rated significantly higher for visibility and effectiveness, with a preference for the 20-foot spacing.
- There was no significant difference among treatments for entry speed.
- The reduction in speed from the tangent to the entry point was significantly greater for the PMDs compared to the baseline “Centerline” but was not statistically different from the other treatments.
- The change in speed variability from the tangent to the entry point for the 20-foot PMDs was greater than the baseline “Centerline,” while it was equivalent or better for the other treatments. Speed variability only narrowed at the entry point for the CWS and PIMs.
- For “long” curves and “large” radius curves, the speed at the midpoint of the curve increased compared to the entry point for the baseline “Centerline” and the CWS, remained relatively unchanged for the edgelines and PIMs, and decreased for the PMDs.
- The PMDs resulted in maximum lateral accelerations that were significantly lower than the baseline “Centerline” but not significantly different from the other treatments.
- There was no difference among treatments on minimum longitudinal acceleration (i.e., braking), but all treatments were significantly better than no treatment.

DISCUSSION

This project undertook a number of tasks in an effort to improve the knowledge and guidance for a number of low-cost delineation measures at VDOT. This section includes discussions relevant to the findings for the district interviews, CMF review, treatment evaluation based on the Smart Road testing, and the selection of the delineation treatments included in the scope of this study.

District Interviews and VDOT Practices Relevant to Low-Cost Delineation

Roadway departure continues to be a focus area in VDOT highway safety planning. However, it appeared to the research team that some district officials are in need of a straightforward approach to identify the most cost-effective measures when selecting low-cost delineation treatments for different cases. The varying CMFs, installation and maintenance costs, and public reception levels for different treatments add complexity to this decision-making process.

District officials that were interviewed identified a large number of factors and facility types for RDCs. Many district officials seemed to believe that roadway departures not only occur at curves but also on straight segments. While focusing on curved roadways appears to yield the most safety benefits, VDOT should not overlook straight segments in the statewide safety improvement process towards zero fatalities.

CMF Review

Overall, the comprehensive review of the CMFs available relevant to a number of low-cost delineation measures showed that some measures have a large number of CMFs available in the literature, while others have limited or no CMFs for practitioners to use. For example, rumble strips, edgelines and centerlines, traditional chevron signs, RPMs, and Safety Edge were found to have a variety of CMFs available. The abundant availability of CMFs for these treatments is potentially due to a combination of factors. Treatments such as rumble strips and Safety Edge have been the subjects of low-cost safety treatments at both the state and federal level for years. They are, therefore, the focus of many safety research projects. In addition, these treatments are commonly used in many states and have sufficient samples for study.

The project team found limited CMFs for CWS with flashing beacons, sequential chevron curve warning systems and PIMs. This is possibly due to the limited use of these treatment measures in most states. Data availability, therefore, becomes a major challenge for the evaluation of such devices. Using CWS with flashing beacons as an example, the project team could only identify a handful of sites across Virginia, which included different types based on site conditions. In addition, PIMs are a relatively new delineation device and therefore have not been the subject of many published studies.

In terms of effectiveness, studies showed fairly consistent safety benefits for treatments such as rumble strips, centerlines and edgelines, curve warning message markings, and chevrons. A majority of the previous studies showed a tangible safety benefit for these devices as evidenced by CMFs below 1. The CMFs for treatments such as RPMs, PMDs, and Safety Edge are relatively mixed, with CMFs above 1 in a number of cases. This finding seems to suggest that the safety effectiveness of these treatments is highly dependent on factors such as site conditions, traffic conditions, and/or weather conditions. They should therefore be a subject for continued research with larger sample sizes and/or better consideration of site conditions. These results in some cases seem to suggest that the use of such treatments should be site specific instead of systemic in order to maximize their safety benefits.

Human Factors Evaluation Results Discussion

Participant Survey Results Discussion

There was a clear subjective preference for the PMDs in the survey results. Participants rated curves with PMDs as more visible and sharper. The height of the posts and their 360-degree visibility allowed them to be seen more easily around curves and up or down hills. It may be that curves were rated as being sharper with PMDs because they allowed participants to better perceive the curvature of the road, or perhaps they imparted a sense that a curve with such treatments must be more "dangerous."

Speed Data Analysis Discussion

Speed is commonly used as a surrogate measure of safety due to the strong relationships between speed and crash experience. Previous studies have shown that speed is one of the most important factors in curve negotiation. Inappropriate speed selection usually results in the inability to maintain lane position, which is the major cause of RDCs. Speeding models have shown that if drivers are speeding in the curve upstream, they will also speed on the curve (Hallmark 2015). Consequently, any countermeasure that affects tangent speed will also decrease the speed in the curve, and thus the importance of delineation treatments.

While the survey data revealed a strong subjective preference for the PMDs among participants, the test track data often showed little objective difference among the tested treatments.

The two PMD spacings did seem to perform better than the other treatments on many factors, but the difference was not typically statistically significant. Of the results that did show a statistical difference among treatments (ignoring the "None" condition), each involved the PMDs performing significantly better than the baseline "Centerline" condition. These included change in speed from the tangent to entry, change in speed from entry to midpoint for "long" curves, and maximum lateral acceleration. At least for these variables, the PMDs were the only treatment to significantly improve performance from the baseline condition, even if their performance was not significantly different from the other treatments.

To look for trends in the data regardless of statistical significance, the performance of each treatment was ranked for each variable, and the average rank was calculated to see how each treatment performed generally across variables (Table 16).

Table 16. Treatment Ranks

Treatment		PMD 40	PMD 20	PIMs	Edgelines	CWS	Centerline
Entry Speed (mph)	Estimate	20.16	20.43	20.52	20.82	20.52	20.32
	Rank	1	3	4	6	4	2
Change in Speed (mph)	Change	-3.02	-3.03	-2.31	-2.5	-1.98	-1.38
	Rank	1	1	4	3	5	6
Speed Deviation (mph)	Change	0.02	0.62	-0.19	0.35	-0.29	0.36
	Rank	3	6	2	4	1	4
Max Lateral Acceleration (g)	Estimate	0.234	0.241	0.247	0.265	0.254	0.273
	Rank	1	2	2	5	4	6
Min Longitudinal Acceleration (g)	Estimate	-0.171	-0.171	-0.176	-0.171	-0.183	-0.178
	Rank	1	1	4	1	6	4
Average Rank		**1.4**	**2.6**	**3.2**	**3.8**	**4**	**4.4**

PMD 40 = Post-mounted delineators at 40-ft spacing, PMD 20 = Post-mounted delineators at 20-ft spacing, PIMs = Plastic inlaid markers, CWS = Curve warning sign.

The 40-foot PMDs had the best average rank of 1.4, followed by the 20-foot PMDs, which had an average rank of 2.6. The "Centerline," which was the baseline condition for most curves, was the worst performer with an average rank of 4.4. This suggests that the addition of any of the other treatments will result in at least marginal improvement in some areas.

The one variable in which the PMDs were among the worst performers was the change in standard deviation of speed from the tangent to the entry. The standard deviation of speed increased for the 20-foot PMDs, while the CWS had the largest decrease. However, the 20-foot PMDs also had the largest reduction in speed and an entry speed that was lower than the CWS. This indicates that the PMDs were better at getting drivers to slow down as they entered the curve, although at different rates, which led to more variability.

Road Characteristics and Limitations

The Smart Roads Rural Roadway used in this study attempts to emulate some of the worst conditions typically found on rural roadways. This includes short sight distances, poor road surface conditions, narrow lanes, sharp horizontal curves, and steep vertical curves. The longest and largest radius curves included in this study are still quite small compared to curves that can be found on rural roadways in Virginia. The average speed at which participants entered a curve was approximately 20 mph. This is quite different from some public roadways where participants might enter a curve at 45 mph or greater. The nature of the test track itself required slower speeds. If these same treatments were tested on larger curves with higher travel speeds, more variation might be found among the treatments.

Discussion on the Selection of Delineation Treatments

The combined results of this study showed the following:

- Among the treatments evaluated, rumble strips, traditional chevron signs, centerlines and edgelines, and curve warning message markings are suitable for systemic application, as evidenced particularly by the overwhelmingly positive CMFs. These devices are well documented in the current MUTCD and are also widely used at VDOT. This finding reaffirms the current VDOT policies relevant to these treatments and therefore requires no or limited changes to current VDOT practices.

- PIMs seemed to particularly benefit in-curve navigation based on the human factors study results. The test results suggested that PIMs were associated with the fewest centerline encroachments during the Smart Road testing. In addition, PIMs were found to generally correlate with a relatively high speed reduction, particularly after entering a curve. These results seem to suggest that PIMs were particularly beneficial for drivers in safely navigating curves.

- A meta-analysis regarding delineator safety was conducted on crashes occurring on rural, two-lane roads (Elvik and Vaa 2004). The results of this study were inconclusive, reporting CMFs of 1.04 ± 0.10 and 1.05 ± 0.07 for injury and property-damage-only crashes, respectively (all CMFs were rated 3 stars). As a follow-on, a combined countermeasure of installing centerlines, edgelines, and PMDs on all roadway types was considered, and this CMF was 0.55 ± 0.11 for injury crashes (CMF is 4 stars). A Korean study (Cho et al. 2017) found that the installation of PMDs on freeways with a minimum AADT of 4,000 and a maximum AADT of 58,000 (4-star rating) increased the crash rate by 19%. More recently, a study from the Kansas DOT (Dissanayake et al. 2017) found that the installation of PMDs on two-lane rural roads resulted in a reduction of 15% of all crashes and in a reduction of 10% of injury crashes. However, the CMF Clearinghouse rated these two CMFs as only 2 stars.

- During the human factors study, PMDs were preferred by participants and associated with more significant effects on driver behaviors. As a result, PMDs seem to be suitable for spot treatment, particularly at isolated curves or curves with limited sight distance. PMDs are more three-dimensional in the sense that they are multiple feet above the ground level and therefore can be viewed with a longer sight distance. They are therefore particularly beneficial for curves that follow long tangents, where drivers can sometimes be less prepared for curves. Curves that have limited sight distances due to vertical alignment features or roadside objects may benefit from PMDs as well.

- The findings from the human factors study regarding PMDs concur with the recently recommended revisions of the MUTCD (Table 17).

Table 17 Proposed Changes to MUTCD Table 2C-5b

Speed Limit (mph)	Devices for Curve Advisory Speed (mph)									
25	25	30	35	40	45	50	55	60	65	70
30	M/W	-	-	-	-	-	-	-	-	-
35	W	M/W	-	-	-	-	-	-	-	-
40	D	W	M/W	-	-	-	-	-	-	-
45	C	D	W	M/W	-	-	-	-	-	-
50	C	C	D	W	M/W	-	-	-	-	-
55	C	C	C	D	W	M/W	-	-	-	-
60	C	C	C	C	D	W	M/W	-	-	-
65	C	C	C	C	C	D	W	M/W	-	-
70	C	C	C	C	C	C	D	W	M/W	-
75 or higher	C	C	C	C	C	C	C	D	W	M/W

M/W – On paved roadways install pavement markings or advanced horizontal alignment warning sign. On unpaved roadways install advance horizontal alignment warning sign.
W – advance horizontal alignment warning sign.
D – delineators plus advance horizontal alignment warning sign.
C – chevrons plus advance horizontal alignment warning sign. Pavement markings may be excluded on unpaved roadways; otherwise, the other provisions of the Table apply.

- The major constraints to developing CMFs for Virginia were data availability and limitations on the number of sites. The research team collected information on all sites with CWS and flashing beacons and sequential flashing beacons. The research team also developed CMF procedures and computed CMFs for the different scenarios for these two treatments, but the number of sites in Virginia was very limited. As the number of sites increases, using the same procedures to develop a new computation is desirable.

- The study results seem to suggest that delineation treatment configuration, particularly spacing, was important for maximizing effectiveness and should be designed to properly indicate curve sharpness. In particular, the spacing for both PIMs and PMDs, as discussed above, should be carefully designed based on the curve radii and potentially vertical curve alignment. When installed 20 feet apart, PMDs were found to be more effective during the human factors study at reducing participants' speeds in multiple cases compared to the 40-foot configuration. Note that all curves used during this human factors study are considered relatively sharp curves and have a low design speed.

- Curve warning message markings received a high priority by district traffic engineers and the TRP, but due to some constraints the TRP decided not to include them in this first stage of evaluation. An evaluation of these types of treatments is recommended as an extension of this project.

CONCLUSIONS

- *The availability of the CMFs for the low-cost delineation treatments varied significantly.* Available CMFs showed that countermeasures have different effects based on the type of crashes treated and site characteristics. The current CMFs in the CMF Clearinghouse suggest that traditional and enhanced chevron signs have the highest potential for crash reductions, followed by rumble strips, pavement markings, and RPMs.

- *The benefit-cost analysis tool allows engineers to compute BCRs not only for all crashes but for specific crashes depending on the availability of CMFs*. This prototype tool provides a comprehensive tool to guide VDOT district traffic engineers in the selection of the most cost-effective delineation treatments based on safety and benefit-cost analyses.

- *PMDs were the most effective treatment evaluated in the human factors study*. Survey data revealed a strong subjective preference for the PMDs among participants. Ratings for curve visibility, treatment effectiveness, curve sharpness, and curve awareness show statistically significant differences between PMDs and other treatments. Based on driver behavior analysis results, PMDs performed significantly better than the baseline "Centerline" condition. However, the human factors study was conducted at speeds lower than are typical for rural roads and may be a limited surrogate for safety measures in these applications.

RECOMMENDATIONS

1. *The VDOT TOD should consider a pilot study of using PMDs for spot treatments at roadway curves where the sight distance is limited.* This is based on the human factors study conducted as part of this project. A potential system-wide screening of suitable locations for PMDs may be conducted to facilitate implementation and maximize safety benefits. VDOT will benefit from the development of PMD CMFs specific to Virginia.

2. *The VDOT TOD should pilot the benefit-cost analysis toolset developed as part of this study as a prototype to aid districts in the process of selecting the most cost-effective delineation measures.* The toolset takes into consideration costs and safety benefits and includes a comprehensive CMF inventory with emphasis on VDOT-preferred CMFs for districts to select. Note that the benefit-cost toolset developed as part of this study only has partial functions as mentioned above.

3. *The VDOT TOD should consider curve warning message markings for evaluation in a second phase.* Curve warning message markings received a high priority for evaluation by district traffic engineers and the TRP but were not included in this project.

4. *The Virginia Transportation Research Council (VTRC) and the TOD should monitor the safety performance and BCRs of chevron signs with flashing beacons and sequential chevron curve warning systems*. When more data and sites become available, studies should be funded to better understand their performances.

5. *VTRC and the TOD should continue to expand the VDOT-preferred CMF list to include a comprehensive list of CMFs for low-cost delineation treatments and for all common site conditions in Virginia*. To identify the high-priority CMFs to include or develop, a potential method is to poll districts for a recommended list of CMFs that are most needed.

IMPLEMENTATION AND BENEFITS

Researchers and the TRP (listed in the Acknowledgments) for the project collaborated to craft a plan to implement the study recommendations and to determine the benefits of doing so. This is to ensure that the implementation plan is developed and approved with the participation and support of those involved with VDOT operations. The implementation plan and the accompanying benefits are provided here.

Implementation

For Recommendations 1-3, the VDOT TOD Assistant Division Administrator for Safety has submitted RNSs to TASRAC for consideration in fall 2022. There is the potential that some installation of treatments may be funded through HSIP systemic two-lane rural road effort. For Recommendation 2, VTRC will provide funding for training on the benefit-cost analysis tool as part of the pilot. TOD, with VTRC assistance, has agreed to monitor the safety performance of chevron signs with flashing beacons and sequential chevron curve warning systems for Recommendation 4. TOD will expand the VDOT-preferred CMF list to include CMFs for low-cost delineation treatments and for all common site conditions for Recommendation 5. A plan for conducting the studies to support the CMF development for Recommendation 5 will be completed within 1 year of the publication of this report.

Benefits

RDCs are a major safety concern at VDOT. VDOT has been devoting significant resources and attention on strategies to prevent such crashes. Implementing the recommendations of this study would fit well into current VDOT safety programs, policies, and initiatives for reducing RDCs. The implementation will result in very limited changes to VDOT policies and business processes and, therefore, will not lead to significant costs to VDOT in addition to those of the ongoing safety efforts as a result. If implemented properly, the recommended actions will result in a better understanding of delineation devices' effectiveness and increased use of more cost-effective delineation treatments, which undoubtedly will lead to higher return in safety investments at VDOT. Two examples illustrate the potential benefit-cost of low-cost delineation. While system-wide safety benefits are highly dependent on the treatment selected and implementation scales, a BCR between 6.8 and 12.1 is estimated using the benefit-cost tool developed as part of this project for using edgelines on two-lane rural roads with an AADT of 5,000, assuming a CMF between 0.8 and 0.9. Similarly, a BCR is estimated between 26 and 67 for using PMDs on a 1,000-foot curve with just one RDC each year on average, assuming a CMF between 0.85 and 0.95.

ACKNOWLEDGMENTS

The authors would like to acknowledge the guidance and contribution from the TRP members on the Implementation section: Mark Cole, Assistant State Traffic Engineer, VDOT TOD (Project Champion); Stephen Read, Highway Safety Planning Manager, VDOT TOD; Brett

Randolph, Assistant District Traffic Engineer, Salem District, VDOT; Keith Rider, District Traffic Engineer, Lynchburg District, VDOT; Michael Fontaine, Associate Director, VTRC; and Benjamin Cottrell, Associate Principal Research Scientist, VTRC.

REFERENCES

AASHTO. *Roadside Design Guide*, 4th Edition. American Association of State Highway Transportation Officials, 2015.

Appiah, J., and Cottrell, B. H. *A Benefit-Cost Analysis Tool for Assessing Guardrail Needs for Two-Lane Rural Roads in Virginia*. Final Report VTRC 16-R5. Virginia Transportation Research Council, October 2015.

Campbell, J. L., Lichty, M. G., Brown, J. L., Richard, C. M., Graving, J. S., Graham, J., O'Laughlin, M., Torbic, D., and Harwood, D. *NCHRP Report 600: Human Factors Guidelines for Road Systems*, Second Edition. National Academies of Sciences, Engineering, and Medicine, 2012. https://doi.org/10.17226/22706.

Carter, D., Srinivasan, R., Gross, F., Himes, S., Le, T., Persaud, B., Lyon, C., Bonneson, J., and Hauer, E. Appendix C: Guidance for Developing Crash Modification Functions. In *Guidance for the Development and Application of Crash Modification Factors*. NCHRP 17-63 Draft Report. The University of North Carolina at Chapel Hill, 2022.

Carter, D., Srinivasan, R., Gross, F., and Council, F. *Recommended Protocols for Developing Crash Modification Factors*. American Association of State Highway and Transportation Officials, February 2012. http://www.cmfclearinghouse.org/collateral/CMF_Protocols.pdf. Accessed 06/02/2020.

Circular A-94: Guidelines and Discount Rates for Benefit-Cost Analysis of Federal Programs. Memorandum for Heads of Executive Departments and Establishments, Office of Management and Budget. https://obamawhitehouse.archives.gov/omb/circulars_a094/a94_appx-c.

Gates, T. J., and Noyce, D. A. *The Safety and Cost-Effectiveness of Bridge-Approach Guardrail for County State-Aid Bridges in Minnesota*. Report No. MN/RC-2005-39. The University of Wisconsin–Madison, October 2005.

Gross, F., Persaud, B., and Lyon, C. *A Guide to Developing Quality Crash Modification Factors*. Report No. FHWA-SA-10-032. VHB, December 2010.

Hallmark, S., Oneyear, N., Tyner, S., Wang B., Charney, C., and McGhee, D. *Analysis of Naturalistic Driving Study Data: Roadway Departure on Rural Two-Lane Curves*. SHRP 2 Report S2-S08D-RW. National Academies of Sciences, Engineering, and Medicine, 2015.

Kweon, Y., and Lim, I. *Development of Safety Performance Functions for Network Screening of Roadway Departure Crashes in Virginia*. Final Report VTRC 19-R12. Virginia Transportation Research Council, February 2019.

Lawrence, M., Hachey, A., Bahar, G., and Gross, F. *Highway Safety Benefit-Cost Analysis Guide*. Report No. FHWA-SA-18-001. VHB, February 2018.

Montella, A. Safety Evaluation of Curve Delineation Improvements: An Empirical Bayes Observational Before-After Study. TRB 88th Annual Meeting Compendium of Papers CD-ROM., Washington, D.C., 2009.

OMB. *Circular A-94: Guidelines and Discount Rates for Benefit-Cost Analysis of Federal Programs*. Memorandum for Heads of Executive Departments and Establishments, Office of Management and Budget. https://obamawhitehouse.archives.gov/omb/circulars_a094/a94_appx-c. Accessed 09/28/2018.

USDOT. *Benefit-Cost Analysis Guidance for TIGER and INFRA Applications*. Office of the Secretary, U.S. Department of Transportation, July 2017.

Virginia Department of Transportation. *Virginia State Preferred CMF List*. https://www.virginiadot.org/business/resources/HSIP/Virginia_State_Preferred_CMF_List.pdf. Accessed 07/12/2022.

APPENDIX A. DISTRICT INTERVIEWS

Included in this appendix are:

- District Interview Questions
- District Poll Results for High-Priority Delineation Measures

Guidance for and Effectiveness of Low Cost Delineation Treatments

Virginia Transportation Research Council Project RNS 19-4

PROJECT BACKGROUND

VDOT recognizes that the selection of countermeasures for roadway departure crashes is a complex process involving a range of factors. It remains challenging for some districts to systematically determine when and where to apply countermeasures to reduce roadway departure crashes and what treatments are most cost beneficial for different traffic and roadway scenarios. The objectives of this research are to:

- Evaluate the safety effects of different low-cost delineation and marking strategies in preventing roadway departure crashes; and
- Determine the life-cycle costs of different treatments identified under the first objective.

Low-cost measures to be considered for evaluation include edge lines with different widths and materials, post-mounted delineators (PMDs) including chevrons with different materials and configurations, and raised pavement markers (RPMs).

DISTRICT INTERVIEW QUESTIONS

1. Roadway departure a safety concern in the district?
   a. Type of roadways where it is a major concern?
   b. Perceived contributing factors for roadway departure crashes?
   c. Major district initiatives to reduce roadway departures?
2. How delineation treatments are selected at the district?
   a. Typical process for use of edge lines, PMDs, and RPMs at VDOT roadways (new construction versus safety projects)?
   b. Warranting factors and analyses, e.g., traffic, roadway, crash, and environmental factors?
   c. Design considerations, e.g., treatment type and configuration?
   d. Benefit cost analyses?
3. Other delineation treatments that are systemically used (e.g., shoulder/edge line/centerline rumble strips, transverse rumble strips, shoulder widening, etc.)?
   a. Alternatives to edge lines, RPMs, and PMDs?
   b. How are alternate treatments selected?
4. Does the district needs additional guidelines or tools for selecting low cost delineation treatments? If yes, what are the needs?
5. How are edge lines, RPMs, and/or PMDs maintained at the district?
6. Can the district identify some study sites with the discussed low cost delineation treatments?
7. Data availability (where to obtain the data):
   a. Location and type of treatments (GIS format?)
   b. Traffic data (counts?)
   c. Cost data (labor, material, contracts, maintenance, etc.).

Figure A1. District Interviews.

Table A1. District Poll Results for High-priority Delineation Measures

Treatment Type	Treatment	Facility Type	No. of Highs	Priority Score
Delineators	Sequential LED chevron signs	Freeways	4	11
Delineators	Static flashing beacon	Multilane	4	10
Delineators	Dynamic speed feedback signs	Multilane	3	10
Delineators	Sequential LED chevron signs	Multilane	3	10
Pavement Markings	Update to increase retroreflectivity	Two-lane	4	10
Pavement Markings	Update to wet pavement markings	Freeways	3	10
Pavement Markings	Curve warning message markings (symbol or slow)	Two-lane	4	10
Delineators	Static flashing beacon	Two-lane	3	9
Delineators	Dynamic speed feedback signs	Two-lane	2	9
Pavement Markings	Update to increase retroreflectivity	Multilane	3	9
Pavement Markings	Update to wet pavement markings	Multilane	3	9
Pavement Markings	Update to wet pavement markings	Two-lane	3	9
Plastic Inlaid Markings	Plastic inlaid markings	Multilane	3	9
Plastic Inlaid Markings	Plastic inlaid markings	Two-lane	3	9
Rumble strips/stripes	Edgeline/shoulder rumble strips	Two-lane	4	9
Delineators	Dynamic speed feedback signs	Freeway	3	8
Pavement Markings	Update to increase retroreflectivity	Freeways	3	8
Pavement Markings	Curve warning message markings (symbol or slow)	Multilane	3	8
Plastic Inlaid Markings	Plastic inlaid markings	Freeways	2	8
Rumble Strips/Stripes	Centerline rumble strips	Two-lane	4	8
Rumble Strips/Stripes	Edgeline/shoulder rumble strips	Multilane	3	8
Rumble Strips/Stripes	Centerline rumble stripes	Two-lane	4	8
Other Treatments	Chevron signs with advisory speed sign on same post	Two-lane	2	8
Delineators	Sequential LED chevron signs	Two-Lane	2	7
Pavement Markings	6” pavement edgeline/lane marking	Two-lane	2	7
Pavement Markings	6” pavement edgeline/lane marking	Multilane	2	7
Rumble Strips/Stripes	Edgeline/shoulder rumble stripes	Two-lane	3	7
Other Treatments	Chevron signs with advisory speed sign on same post	Multilane	1	7
Rumble Strips/Stripes	Edgeline/shoulder rumble strips	Freeways	2	6
Rumble Strips/Stripes	Edgeline/shoulder rumble stripes	Multilane	2	6
Other Treatments	Chevron signs with advisory speed sign on same post	Freeways	2	6
Delineators	Chevron (oversized)	Multilane	0	5
Delineators	Chevron (oversized)	Two-lane	0	5
Pavement Markings	Thermoplastic/different types of pavement marking	Multilane	2	5
Rumble Strips/Stripes	Centerline rumble strips	Multilane	2	5
Other Treatments	Elongated curve warning message markings	Two-Lane	2	5

Number of Highs is the count of districts who considered the treatment high priority. Priority score is calculated as the sum of priority ratings of all districts. For each treatment, a high priority is assigned with a score of 3, a medium priority is assigned with a score of 2, and a low priority is assigned with a score of 1.

APPENDIX B. BENEFIT-COST ANALYSIS METHODOLOGY FOR COST ESTIMATION

Crash Cost Estimates

Crashes prevented by adding or improving lighting at intersections are considered safety benefits. Table B1 lists the average crash unit cost estimates both for Virginia and nationwide. The project team was able to identify two versions of Virginia crash cost estimates from different sources and neither was broken down by cost items. The national estimates included estimates for both economic costs of the crashes and quality-adjusted life year (QALY) costs. Note: The crash unit cost estimates were for all crashes regardless of crash type, time, and location. The project team was not able to obtain crash unit cost estimates for nighttime intersection crashes for either Virginia or the entire nation.

Table B1. Average Crash Unit Cost by Severity – Virginia and National Data

Type		K	A	B	C	O	Year
VA[1]	-	$4,008,885	$216,059	$56,272	$56,272	$7,428	2001
VA[2]	-	$5,241,924	$280,664	$102,604	$58,132	$9,512	2012
National[1]	Economic	$1,722,991	$130,068	$53,700	$42,536	$11,906	2016
	QALY	$9,572,411	$524,899	$144,792	$83,026	$0	
	Total	**$11,295,402**	**$654,967**	**$198,492**	**$125,562**	**$11,906**	

[1]Harmon et al. 2018; [2]CMF Clearinghouse 2020

During this study, the project team converted the Virginia crash unit costs to 2019 values based on the procedures recommended by the *Highway Safety Manual* (AASHTO 2010). The procedure recommends that crash costs of a certain year be adjusted to a target year by adjusting the direct economic costs and the QALY costs based on the corresponding Consumer Price Indices (CPIs) and Employment Cost Indices (ECIs), respectively:

$$CUC_{target} = ECUC_{data} \times \frac{CPI_{target}}{CPI_{data}} + QCUC_{data} \times \frac{ECI_{target}}{ECI_{data}}$$

Where:

CUC_{target} = target year total crash unit cost by severity;
$ECUC_{data}$ = data year economic crash unit cost by severity;
$QCUC_{data}$ = data year QALY crash unity cost by severity;
CPI_{target} = target year CPI;
CPI_{data} = data year CPI;
ECI_{target} = target year ECI; and
ECI_{data} = data year ECI.

During this project, the team did not obtain separate economic and QALY crash unit cost data for Virginia. The project team, therefore, obtained the economic and QALY portions of the Virginia crash unit cost estimates by applying the corresponding percentages based on the national estimates, as shown in Table B2.

Table B2. Determination of Economic and QALY Crash Costs for Virginia

Type		K	A	B	C	O
National	Economic	$1,722,991	$130,068	$53,700	$42,536	$11,906
	Economic %	15.25%	19.86%	27.05%	33.88%	100.00%
	QALY	$9,572,411	$524,899	$144,792	$83,026	$0
	QALY %	84.75%	80.14%	72.95%	66.12%	0.00%
	Total	$11,295,402	$654,967	$198,492	$125,562	$11,906
VA 2001	Total	$4,008,885	$216,059	$56,272	$56,272	$7,428
	Economic	$611,512	$42,907	$15,224	$19,063	$7,428
	QALY	$3,397,373	$173,152	$41,048	$37,209	$0
VA 2012	Total	$5,241,924	$280,664	$102,604	$58,132	$9,512
	Economic	$799,599	$55,736	$27,758	$19,693	$9,512
	QALY	$4,442,325	$224,928	$74,846	$38,439	$0

Using the historical ECI and CPI data shown in Table B3, the project team estimated the Virginia crash unit costs by severity as shown in Table B4.

Table B3. Historical ECI and CPI Values

Year	ECI*[1]	CPI**[2]
2001	85.5	175.6
2012	116.8	227.842
2016	126.7	237.652
2020	140.6	258.687

* June values for all civilian workers.

**Annual average values for all items in Census South Region, all urban consumers, not seasonally adjusted.

[1]BLS 2021a; [2]BLS 2021b

Table B4. 2020 Virginia Crash Unit Costs by Severity Based on 2001 and 2012 Estimates

Type		K	A	B	C	O
2020 Estimates based on 2001 data	Economic	$900,855	$63,209	$22,427	$28,083	$10,943
	QALY	$5,586,791	$284,739	$67,501	$61,188	$0
	Total	$6,487,647	$347,948	$89,929	$89,271	$10,943
2020 Estimates based on 2012 data	Economic	$694,298	$48,716	$17,285	$21,644	$8,434
	QALY	$5,347,525	$270,761	$90,097	$46,272	$0
	Total	$6,041,823	$319,477	$107,382	$67,915	$8,434
Average 2020 Estimates		**$6,264,735**	**$333,712**	**$98,655**	**$78,593**	**$9,688**

The benefit-cost analysis was performed for all crashes regardless of severity outcomes. The project team, therefore, had to convert the severity-specific unit crash cost estimates to unit costs to crashes of all severity levels. For this purpose, the project team obtained the average crash unit cost weighted by the crash proportions of individual severity levels as following:

$$CUC_{all} = CUC_K \times P_K + CUC_A \times P_A + CUC_B \times P_B + CUC_C \times P_C + CUC_O \times P_O$$

Where:

CUC_{all} = overall crash unit cost regardless of crash severity;

CUC_i = crash unit cost for severity *i* (e.g., CUC_K is the unit cost of fatal crashes);

and

P_i = proportion of crashes of severity *i* (e.g., P_O is the proportion of PDO crashes in the overall crash population) in the overall crash population.

To estimate the proportions of crashes by severity, the project team used the 5-year (2014–2018) RDCs based on the VDOT crash data. Table B5 contains the crash proportions by severity level. Based on these proportions, the project team estimated the overall crash unit cost regardless of severity as $108,065.86 (2020 dollars). Similarly, the overall average unit cost for fatal and injury (KABC) crashes was estimated as $278,717.14, and the overall average unit cost for injury (ABC) crashes was estimated as $148,660.73.

Table B5. Proportions of RDCs by Severity (VDOT 2014–2018)

Severity	Count	Percent
K – Fatal Injury	114	0.78%
A – Severe Injury	1,191	8.10%
B – Visible Injury	3,180	21.62%
C – Non-visible Injury	876	5.96%
O – Property Damage Only	9,348	63.55%
Total	14,709	100.00%

Safety Treatment Cost Estimates and Life Cycles

Converting Past Costs to Current Values

Some cost estimates associated with the analyzed safety treatments, such as construction/installation costs and annual maintenance costs used in this study, were entirely or partially based on historical data published in previous studies. These cost estimates needed to be converted to the current year (e.g., 2019) costs prior to the benefit-cost analysis. Currently, there are a variety of indices and methods that can be used for converting past dollar values to current dollar values. Examples of such indices include the CPI, with a 1.96% annual increase for the period between 2001 and 2020 (US Inflation Calculator 2018), and the ECI, with an annual increase of 2.43% (for the construction, extraction, farming, fishing, and forestry industries) between 2002 and 2020 on average (BLS 2019).

Note that the construction and maintenance costs of the evaluated transportation infrastructure categories typically include both labor and material costs, which makes the use of CPI and/or ECI less accurate. CPI measures the average change in the prices paid by urban consumers for a market basket of consumer goods and services, while ECI measures the changes in labor costs over time. To better reflect highway-related materials and construction costs, the project team used the National Highway Construction Cost Index (NHCCI) for this purpose. FHWA publishes the NHCCI to measure the average changes in the prices of highway construction costs over time (FHWA 2020a). The index is determined based on winning bids submitted on highway construction contracts at state transportation agencies. Between 2003 and 2020, the NHCCI increased 5.70% on average annually (Table B6).

Table B6. 2003–2020 NHCCI (FHWA 2018)

Year	NHCCI Index	Percent Increase
2003 Q1	1.000	-
2004 Q1	1.046	4.59%
2005 Q1	1.241	18.64%
2006 Q1	1.449	16.74%
2007 Q1	1.564	7.94%
2008 Q1	1.569	0.32%
2009 Q1	1.500	-4.38%
2010 Q1	1.442	-3.87%
2011 Q1	1.457	1.03%
2012 Q1	1.577	8.24%
2013 Q1	1.591	0.88%
2014 Q1	1.628	2.32%
2015 Q1	1.720	5.65%
2016 Q1	1.631	-5.15%
2017 Q1	1.617	-0.85%
2018 Q1	1.675	3.55%
2019 Q1	1.849	10.42%
2020 Q1	1.969	6.46%
Average	-	**5.70%**

Rumble Strips

Costs of rumble strips estimated by previous studies varied significantly based on factors such as installation method, pavement type, location, and configuration. The installation cost of rolled rumble strips, for example, is typically minimal and sometimes not billed separately during pavement construction. Rolled rumble strips refer to rounded or V-shaped grooves pressed into asphalt pavement when it is still hot in the course of paving projects. However, FHWA does not recommend the use of rolled rumble strips (FHWA 2020b). This study focused on the costs associated with milled rumble strips, which are uniform grooves cut into cold pavement by a machine with a rotary cutting head.

VDOT specifications require that both shoulder and centerline rumble strips be milled-in and cylindrical (VDOT 2020). Shoulder rumble strips are typically 9-inches wide and centerline rumble strips are 14-inches wide as required by VDOT specifications. For milled-in rumble strips, VDOT requires that liquid asphalt coating be applied on all centerline rumble strips and on shoulder/edgeline rumble strips that are not installed on new pavement.

The VDOT 2019–2021 statewide average bid prices indicated an average unit (linear foot) cost of $0.36 for cylindrical rumble strips on asphalt pavement (VDOT Pay Item 10700) and a per square yard cost of $1.06 for liquid asphalt rumble strip coating. Using these averages, the team estimated the following average unit costs for rumble strips:

- Centerline rumble strips (including installation and sealing): $0.36 + $1.06 ÷ [(1296 ÷ 18) ÷ 12] = $0.54 assuming the rumble strips are 14-inches wide and sealing coat spills 2 inches out on each side. Note that centerline rumble strips installed on existing pavement may require restriping as they frequently overlay with centerline markings.
- Shoulder/edgeline rumble strips on new pavement: $0.36.

- Shoulder/edgeline rumble strips on existing pavement: $0.36 + $1.06 ÷ [(1296 ÷ 13) ÷ 12] = $0.49 assuming the rumble strips are 9-inches wide and sealing coat spills 2 inches out on each side.

Edgelines and Centerlines

VDOT uses a number of different permanent pavement marking types based on applications as specified in the VDOT *Traffic Engineering Design Manual* (VDOT 2014a):

- Type A – traffic paint;
- Type B, Class I – thermoplastic pavement marking material;
- Type B, Class II – preformed thermoplastic pavement marking material;
- Type B, Class III – epoxy-resin pavement marking material;
- Type B, Class IV – plastic-backed preformed tape;
- Type B, Class VI – patterned (profiled) preformed tape; and
- Type B, Class VII – polyurea pavement markings.

Depending on factors such as material type, width, contract size, and contractor used, pavement marking costs vary significantly. The service lives for different marking materials also vary based on how well the markings are installed and the traffic and environmental conditions. For example, snowplowing activities can considerably reduce pavement marking service lives.

Table B7 lists the pavement marking installation costs and service lives based on a literature review.

Table B7. Installation Costs and Service Lives for Pavement Markings

Source	Material Type	Marking Width	Cost	Service Life	Year
Literature review and survey (Miller 1993)	High-solvent paint	Not specified. All solid single stripes.	$0.035/ft for rural $0.07/ft for urban	6 months on interstates, other freeways, and major urban arterials; 1 year on other roads.	1993
	Thermoplastic	Not specified. All solid single stripes.	$0.26/ft for rural $0.33/ft for urban	5 years	1993
MnDOT (Montebello and Schroeder 2000)	Latex or alkyd-new formula	Not specified	$0.03-0.05/ft	9-36 months	2000
	Mid-durable paint	Not specified	$0.08-0.10/ft	9-36 months	2000
	Epoxy	Not specified	$0.20-0.30/ft	4 years	2000
	Tape	Not specified	$1.50-2.65/ft	4-8 years	2000
	Preformed thermoplastic	Not specified	-	3-6 years	2000
NCDOT (Howard et al. 2015)	Paint		$0.24/ft		2015
	Extruded thermoplastic	4”	$0.62/ft for 90 mil $0.72/ft for 120 mil		2015
	Polyurea		$0.65/ft		2015
Literature review (bid price) (Pike et al. 2018)	Paint	4”	$0.05-0.22/ft	1 year	2018
		6”	$0.08-0.53/ft	1 year	2018
	Thermoplastic	4”	$0.11-0.91/ft	3-4 years	2018
		6”	$0.16-1.08/ft	3-4 years	2018
	Epoxy	4”	$0.30-1.32/ft	3-4 years	2018
		6”	$0.54-0.69/ft	3-4 years	2018
	Tape	4”	$1.94-3.78/ft	6 years	2018
		6”	$2.08-5.62/ft	6 years	2018
	Polyurea	4”	$0.56-1.32/ft	3-4 years	2018
		6”	$0.80/ft	3-4 years	2018
	Methyl methacrylate	4”	$1.25/ft	-	2018
		6”	$0.79-0.80/ft	-	2018
VDOT (Cottrell and Hanson 2001, Fontaine and Gillespie 2009)	Paint		$0.04-0.15/ft	1 year	2001
	Thermoplastic		$0.35/ft	3 years	2001
	Epoxy		$0.40/ft	3 years	2001
	Polyurea		$0.70/ft	3 years	2001
	Patterned preformed tape		$1.80/ft	6 years	2001

As part of this project, the team also requested cost data directly from VDOT. Table B8 shows the average unit costs extracted by VDOT based on 2019–2021 statewide bid data relevant to pavement markings.

Table B8. VDOT 2019–2021 Statewide Average Bid Prices for Pavement Markings

Item	Item Description	Unit	Min	Max	Average
54020	TYPE A PVMT LINE MRKG 4"	LF	$0.05	$12.00	$0.08
54022	TY A PVMT LINE MRKG 6"	LF	$0.01	$38.00	$0.10
54024	TYPE A PVMT LINE MRKG 8"	LF	$0.10	$2.00	$0.21
54026	TYPE A PAVEMENT LINE MRKG 12"	LF	$0.23	$21.00	$0.24
54028	TYPE A PAVEMENT LINE MRKG 24"	LF	$0.80	$33.00	$5.22
54032	TYPE B CLASS I PVMT LINE MRKG 4"	LF	$0.01	$47.85	$0.53
54034	TY B CL I PVMT LINE MRKG 6"	LF	$0.55	$45.73	$0.84
54037	TYPE B CLASS I PVMT LINE MRKG 8"	LF	$0.60	$46.30	$1.46
54040	TY B CL I PVMT LINE MRKG 12"	LF	$1.75	$48.42	$3.17
54042	TY.B CL.I PAVE. LINE MARK. 24"	LF	$3.15	$150.00	$7.86
54043	TY.B CL.II PAVE. LINE MARK. 4"	LF	$1.65	$11.00	$4.12
54044	TY.B CL.II PAVE. LINE MARK. 6"	LF	$1.85	$12.54	$2.24
54045	TY.B CL.II PAVE. LINE MARK. 8"	LF	$5.67	$10.00	$6.51
54047	TY.B CL.II PAVE. LINE MARK. 12"	LF	$8.65	$43.20	$13.69
54048	TY.B CL.II PAVE. LINE MARK. 24"	LF	$5.00	$54.00	$17.54
54049	TY.B CL.III PVMT LINE MRKG 4"	LF	$4.62	$4.62	$4.62
54050	TY.B CL.III PVMT LINE MRKG 6"	LF	$10.50	$10.50	$10.50
54055	TY.B CL.IV PVMT LINE MRKG 4"	LF	$3.50	$3.50	$3.50
54056	TY.B CL.IV PVMT LINE MRKG 6"	LF	$4.76	$4.76	$4.76
54060	TY.B CL.IV PVMT LINE MRKG 24"	LF	$16.00	$22.50	$17.77
54075	TY.B CL.VI PVMT LINE MRKG 4"	LF	$1.00	$20.00	$2.84
54076	TY.B CL.VI PVMT LINE MRKG 6"	LF	$1.00	$6.00	$3.38
54077	TY.B CL.VI PVMT LINE MRKG 8"	LF	$2.50	$9.45	$4.68
54078	TY.B CL.VI PVMT LINE MRKG12"	LF	$4.60	$16.00	$7.73
54079	TY.B CL.VI CONTRAST PVMT MRKG, 4"	LF	$1.00	$9.00	$4.92
54080	TY.B CL.VI CONTRAST PVMT MRKG, 6"	LF	$1.00	$18.65	$5.45

Note that pavement markings generally do not have maintenance costs. The service lives for markings are considered as the period from their initial installation to reinstallation. The VDOT-provided pavement marking costs were generally comparable to those found in the literature review. For this project, the team used the VDOT-provided estimates for the service lives (Cottrell and Hanson 2001).

Curve Warning Message Markings Curve warning message markings can have several configurations, including “CURVE”, a curve arrow, “SLOW,” advisory speed, an elongated advisory speed, and optional white bars. Therefore, the costs of curve warning message markings can vary from case to case. The costs of pavement marking installations also vary considerably based on the number of sites included, if the contract is a part of a larger project, or the marking materials used. Considering that the application of curve warning message markings are frequently on a case-by-case basis and mostly on non-freeways, the project team used the average price for 54401 – School Zone marking in Table B9 as a reasonable price estimate for curve warning message marking installation cost. According to the 2019–2021 statewide average bidding prices, the cost for applying a curve warning message marking is $1,082.66. Similar to pavement line markings, this project assumed a service life of 3 years for curve warning message marking.

Table B9. Sample VDOT Bid Items and Average 2019–2021 Prices Similar to On-pavement CWS

Item Code	Description	Unit	Min Price	Max Price	Average Price
54255	PVMT MESSAGE, 6’, CHARACTER, TY. A	EA	$12.00	$12.00	$12.00
54256	PVMT MESSAGE, 6’, CHARACTER TY. B,CL.I	EA	$350.00	$350.00	$350.00
54257	PVMT MESSAGE, 6’, CHARACTER TY. B,CL.II	EA	$320.24	$347.84	$334.04
54261	PVMT MESSAGE, 8’, CHARACTER TY. B,CL.I	EA	$100.00	$150.00	$107.41
54262	PVMT MESSAGE, 8’, CHARACTER TY. B,CL.II	EA	$55.63	$408.79	$278.18
54266	PVMT MESSAGE, 10’, CHARACTER TY. B,CL.I	EA	$300.00	$300.00	$300.00
54391	PVMT MSG. MARK. ?ONLY? TY A, 6?	EA	$100.00	$100.00	$100.00
54392	PVMT MSG. MARK. ?ONLY? TY B, CL. I,	EA	$100.00	$567.07	$180.18
54393	PVMT MSG. MARK. ?ONLY? TY B, CL II,	EA	$255.44	$912.00	$608.11
54395	PVMT MSG. MARK. ?SCHOOL? TY B, CL I,	EA	$380.00	$1,400.00	$747.14
54396	PVMT MSG. MARK. ?SCHOOL? TY B, CL II	EA	$580.00	$1,944.00	$1,138.29
54400	PVMT MESSAGE MARK. ONLY	EA	$6.00	$750.00	$373.94
54401	PVMT MESSAGE MARK. SCHOOL ZONE	EA	$325.00	$1,935.00	$1,082.66
54570	PVMT SYMB MRKG THRU ARROW TY A	EA	$81.00	$81.00	$81.00
54571	PVMT SYMB MRKG THRU ARROW TY B, CL I	EA	$60.00	$535.59	$104.42
54572	PVMT SYMB MRKG THRU ARROW TY B, CL II	EA	$245.00	$429.30	$321.15
54573	PVMT SYMB MRKG SGL TURN ARROW TY A	EA	$38.50	$1,500.00	$129.93
54574	PVMT.SYMB MRKG SGL TURN ARR. TY B CL I	EA	$49.00	$950.00	$112.37
54575	PVMT SYMB MRKG SGL TURN ARR. TY B CL II	EA	$2.35	$719.63	$310.94
54576	MRKG DBL TURN ARR. THRU/LT OR RT TY A	EA	$48.00	$1,200.00	$119.32
54581	PVMT SYMB MRKG TRPL TURN ARR TY B, CL I	EA	$200.00	$378.00	$277.38
54582	PVMT SYMB MRKG TRPL TURN ARR TY B CL II	EA	$225.92	$950.00	$573.16
54585	SYMB MRKG DBL TURN ARR LT/RT TY.B CL I	EA	$145.00	$870.00	$246.54
54586	SYMB MRKG DBL TURN ARR LT/RT TY.B CL II	EA	$340.00	$526.57	$470.18
54622	PVMT SY MRK YLD (1?x 1.5?) TY B, CL	EA	$28.38	$65.00	$31.73
54625	PVMT SYMB MRKG YIELD (2?x 3?) TY B,	EA	$24.00	$106.40	$57.57
54626	PVMT SY MRK YLD (2?x 3?) TY B, CL II	EA	$47.65	$115.00	$89.95

Post-mounted Delineators

A literature review showed very limited information on cost estimates of PMDs. A 2012 study based on Texas data suggested a cost of $30/each for pylon flexible PMDs mounted at a 10-foot spacing configuration (Kuchangi et al. 2013). An Illinois study recommended a service life of 4 years for roadside PMDs and 1 year for PMDs installed on the pavement (ILDOT 2017). Another study based on Michigan data, however, suggested an average service life of 7 years for roadside PMDs with a range between 4 and 10 years (Ceifetz et al. 2017). The Michigan study also suggested an average unit cost of $30 each (ranging between $19 and $48) for the PMDs. For this project, VDOT showed an average unit cost of $59.22 with a minimum price of $28.80 and a maximum price of $210.00 based on recent (2019–2021) statewide bid prices for flexible post delineators (pay item 24286).

When installing PMDs, MUTCD (FHWA 2012) recommends that the delineators be placed 200 to 530 feet apart on mainline tangent sections or 100 feet apart on ramp tangent sections. On horizontal curves, the spacing for delineators should be determined based on the curve radius roughly following the formula:

$$S = 3\sqrt{r - 50}$$

where S is the spacing for PMDs and r is the curve radius. The calculated spacing is typically rounded to the nearest 5 feet and should be between 20 feet and 300 feet regardless of curve radius.

In addition to the installation costs discussed above, the project team found very limited information on maintenance costs for PMDs. A previous Texas study (Srinivasan et al. 2009) based on the pylon PMDs installed on Katy Freeway for separating HOT lanes suggested that the PMDs required monthly maintenance. For roadside PMDs, the project team did not obtain information on maintenance frequency and cost. Note that crashes involving PMDs are mostly minor property-damage-only crashes that are not reported to police. Therefore, states can rarely recover the costs for PMDs from insurance companies. In addition, maintenance practices among different states and districts within the same states vary significantly. For this project, the team assumed a 3-year service life for roadside PMDs.

Chevrons

The MUTCD specifies a number of different sizes and configurations for chevron signs (FHWA 2012). Standard chevron signs vary from 12 × 18 inches to 36 × 48 inches based on applications. Sign spacing for chevron sign arrays varies from 40 feet to 200 feet in a 40-foot increment based on advisory speed and curve radius. Table B10 shows the limited cost information for chevron signs found from a literature review. The cost estimates from different studies vary significantly. The project team also obtained the following costs from VDOT based on sample projects:

- 24 × 30 chevron signs (oversized): $50.00 each
- 36 × 48 chevron signs (for use on freeways): $118.00 each
- Sign posts: $24/ft for STP-1, 2 ½", 12-gauge poles

For this project, based on the data available, the team used a total unit cost of $290 for the initial installation of chevron signs. This cost estimate includes a 24 × 30 sign panel and a 10-foot post. Note that the length of posts for chevron signs varies in the field based on where and how the signs are installed. For freeways, the project team estimated a total unit cost of $358 based on 37 × 48 inch sign panels. The project team did not obtain maintenance costs associated with chevron signs. Interviews with VDOT districts suggested that maintenance practices with signs vary significantly among different districts. Some districts conduct routine inspections of the signs while others only fix them when signs are reported damaged. In addition, the service life of the signs can vary significantly. If not damaged, the signs may stay in service for a long period. Considering the limited information obtained and VDOT feedback, this project assumed an average service life of 10 years for chevrons.

Table B10. Cost and Service Life Information for Chevron Signs from Literature

Source	Cost	Cost Year	Service Life
Washington and Connecticut (Srinivasan et al. 2009)	$100/each ($30 to $160/each)	2009	
Not specified. Study based on 23 states (Carlson et al. 2020)	$198/each ($88 for sign and $110 for installation)	2015	11.1 years
Not specified (McGee and Hanscom 2006)	$50/each for basic signs $335/each for 18 × 24 signs with Type III sheeting $343/each for 18 × 24 signs with Type III sheeting and fluorescent color	2006	

In terms of sign spacing, the MUTCD recommends the following spacing for chevron signs (Table B11).

Table B11. Spacing Recommendations for Chevron Signs on Horizontal Curves (FHWA 2014)

Advisory Speed	Curve Radius	Sign Spacing
15 mph or less	Less than 200 feet	40 feet
20 to 30 mph	200 to 400 feet	80 feet
35 to 45 mph	401 to 700 feet	120 feet
50 to 60 mph	701 to 1,250 feet	160 feet
More than 60 mph	More than 1,250 feet	200 feet

Curve Warning with Flashing Beacons

The costs of signs with flashing beacons vary significantly based on the type of signs, quantity, installation method and structure, power source, and power supply availability. VDOT statewide average bid data (2019–2021) showed a total cost of $3,904.71 per sign with flashing beacons attached (i.e., VDOT classification FB-2), with a minimum of $1,999.00 and a maximum of $19,000.00 per unit. The data obtained from VDOT, however, did not specify the type of signs and flashing beacons. The VDOT standard flashing beacons (FB-2) require two beacons attached on top of the sign post and available electricity supplies (VDOT 2019a). Modern solar-powered LED systems do not require existing power supplies and may be available for a lower price.

During this project, the research team did not identify additional cost estimates for flashing beacons from other sources after an extensive literature review. In addition, the team did not obtain estimates of maintenance costs and the service life for signs with flashing beacons. The maintenance of CWS with flashing beacons may include routine inspections, replacement of signs, replacement of lamps, replacement of other flashing beacon-related components (e.g., battery if solar powered), and replacement of the entire structure if damaged by traffic crashes. The maintenance costs, therefore, may vary significantly based on the nature of the work performed. Given the lack of maintenance data, the project team assumed a conservative service life of 5 years in an attempt to reflect the potential maintenance costs associated with flashing beacons.

Sequential Chevron Curve Warning System

Sequential chevron curve warning systems may operate at fixed intervals throughout the entire day, at fixed intervals from dusk to dawn, or after actuation when an approaching vehicle is detected. Depending on how they operate, the system may require light sensors or radar detectors in order to be actuated. Therefore, the costs associated with such systems may vary significantly. During this study, the project team obtained extremely limited cost information from the existing literature and VDOT bid information. A VDOT engineer, however, estimated the material cost for sequential LED chevron signs at $3,200 per sign. In terms of maintenance and service life, since sequential chevron systems are commonly powered by solar energy, the LEDs and electric components may require relatively frequent inspection and replacement compared to the signs and the structural components. Due to a lack of information, this project assumed a 10-year service life with no maintenance costs.

Raised Pavement Markers

The safety benefit-cost and performance of traditional RPMs have been a research focus for years. Table B12 lists the cost estimates and service lives based on a literature review. The costs of RPMs in general include materials, initial installation, and maintenance. In addition, different installation configurations (e.g., spacing) also significantly affect the per-mile cost for RPMs. The MUTCD recommends RPM spacing ranging from 20 feet to 80 feet for most applications depending on roadway type, installation location (e.g., centerline versus lane marking), and curve radius (FHWA 2012).

Table B12. Costs and Service Lives for RPMs based on Literature Review

Source	Cost	Cost Year	Service Life
Michigan (ILDOT 2020)	$6/each ($4-$11) for regular RPMs $38/each ($31-$55) for snowplowable RPMs	2017	4 years (2-6 years) for regular RPMs 6 years (2-10 years) for snowplowable RPMs
Not specified (FHWA 2009)	$50/each for LED RPMs	2009	
Multistate (Liu et al. 2018)	$2.40-$23/each	2018	4-10 years for snowplowable RPMs
Indiana (Jang 2006)	$13-$20/each (lens replacement $3.30-$8/each)	2006	1-4 years based on traffic volume (Indiana and Texas data)
Indiana (Gartner et al. 2016)	$280/each for initial installation, $320/each lifetime cost including maintenance	2016	
Maryland (Ceifetz et al. 2017)	$38/each for initial installation, $9/each for lens replacement, $65/each total lifetime cost including maintenance	2016	2 years for lenses
Ohio (Ceifetz et al. 2017)	$20/each for initial installation, $2.80/each for lens replacement	2016	3 years for lenses, 10-12 years for casting
South Carolina (Ceifetz et al. 2017)	$320/each lifetime cost including $50/each for maintenance	2016	3 years for non-interstates and 2 years for interstates
Texas (Ceifetz et al. 2017)	$33.61/each for initial installation	2016	
Virginia (Ceifetz et al. 2017)	$15/each for initial installation	2016	
Vermont (Paterson and Fitch 2007)	$8.10/each for material and $60/each for installation, $3.75/each for lens replacement	2006	3-5 years
Missouri (Bahar et al. 2004)	$42.50/each	2004	

Table B13 further lists the initial installation costs for RPMs (including materials) based on 2019–2021 statewide bid data at VDOT. In general, the costs are within the range of the estimates identified in the literature review. This project adopted the following cost and service lives based on the VDOT data:

- Snowplowable RPM initial installation (including materials): $30.65 (with a minimum of $10 and a maximum of $434.50) each if on asphalt and $62.59 (with a minimum of $25.00 and a maximum of $300.00) each if on concrete (VDOT 2021).
- Lens replacement: $9.18 each.
- Service life for snowplowable RPMs: 10 years (VDOT repaving cycle) for casting, 2 years for lens on freeways, and 3 years for lens on other roadways.

Table B13. VDOT Initial Installation Cost Data for RPMs

Item	Item Description	Unit	Min	Max	Average	Year
54210	Rem Exist Raised Pave. Marker	Ea.	$3.63	$296.10	$25.94	2019-2021
54216	Repl Lens Snow Plow Raised Marker	Ea.	$7.20	$20.00	$9.18	2019-2021
54217	Snow Plow Raised Pave Mark Asph Conc	Ea.	$10.00	$434.50	$30.65	2019-2021
54218	Snow Plow Raised Pave Mark Hyd Conc	Ea.	$25.00	$300.00	$62.59	2019-2021

Plastic Inlaid Markers

VDOT estimated an average unit cost of $39.82 (with a minimum of $22.20 and a maximum of $310.00) for PIMs on asphalt pavement or $44.85 (with a minimum of $39.00 and a maximum of $85.50) for PIMs on concrete pavement based on the latest 2-year statewide average bidding prices (last updated April 5, 2021). The cost includes surface preparation, furnishing, installing, retroreflectors, pavement cutting, adhesives, and holder according to VDOT specifications (Figure 33) (VDOT 2019b). The PIM installation would include an additional $30 per PIM if sealing is required (Nguyen 2020). In addition, a review of the publicly available bid data at the Kentucky Transportation Cabinet showed an average cost of $25.53 per PIM in 2020 based on 38 contracts, $27.73 per PIM in 2019 based on 51 contracts, $29.84 per PIM in 2018 based on 30 contracts, and $35.01 per PIM in 2017 based on 56 contracts (with a weighted average of $29.94 per PIM for the 4-year period) (KTC 2021a). These bid prices seemingly suggest a declining trend for PIM installation and materials over time. Note that the lower unit costs from Kentucky data do not necessarily indicate lower installation costs. Kentucky Transportation Cabinet requires two PIMs per groove (KTC 2021b), effectively lowering the grooving costs for each PIM.

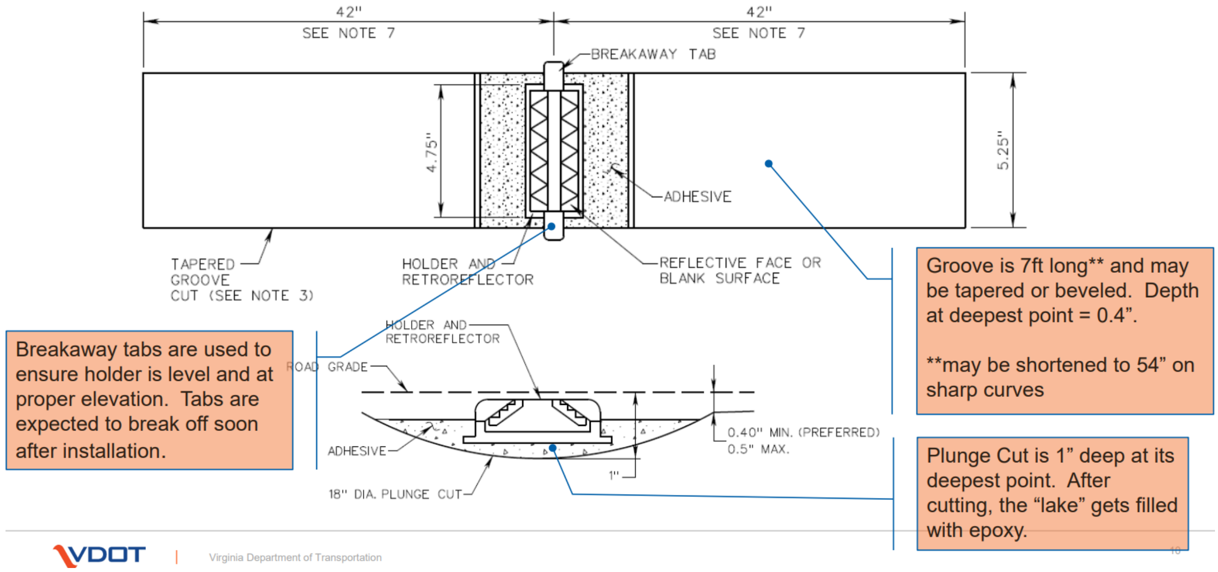


Figure 33. VDOT PIM Installation Specification (KTC 2021b).

The *Virginia Supplement to the MUTCD* specifies 40-foot maximum spacing between PIMs supplementing solid pavement marking lines and 80-foot maximum spacing for PIMs supplementing broken line markings (VDOT 2014b). The document also specifies that shorter spacing may be used at certain locations based on engineering judgement, such as intersection approaches and ramp locations. Note that when used on roadway segments, PIMs are generally used for all lane markings, including centerlines.

For this project, the team used the VDOT estimate ($39.82 per PIM assuming asphalt pavement) for the cost estimation. In order to estimate the number of PIMs required on a per-mile basis, however, users should have knowledge of the type of applications (e.g., spacing and layout of the PIMs). Based on VDOT recommendations, this study assumed a service life of 3 years for PIMs. Note that grooving is not required when replacing existing PIMs without resurfacing pavement. For this reason, replacing existing PIMs without resurfacing (i.e., in between pavement resurfacing cycles) should cost less. The VDOT bid database currently does not include prices for replacing existing PIMs. For the purpose of this project, however, the team used the statewide average unit cost of removing existing RPMs as a surrogate cost for replacing PIMs. The latest VDOT statewide bid data indicated an average unit cost of $25.94 (with a minimum of $3.63 and a maximum of $296.10) for removing existing RPMs.

Safety Edge

There were limited cost estimates for Safety Edge found in the literature. A 2011 FHWA study estimated the costs for Safety Edge to be $536/mile for 1.5-inch overlays and $2,145/mile for 3.0-inch overlays (Graham et al. 2011). The VDOT 2019–2021 statewide bid data showed an average of $0.39 per foot for pavement shoulder wedge preparation (Pay item 10706), which translates to $2,059.20 per mile for a single pavement edge or $4,118.40 per mile for both pavement edges. The VDOT data, however, did not include information on the type of pavements. For this project, the team adopted the VDOT average costs for Safety Edge. The team also assumed the life cycle of Safety Edge to be the same as the paving cycle at VDOT, which is 10 years. The project did not consider maintenance costs for Safety Edge.

Cost Estimation Summary

Table B14 summarizes the unit costs for the delineation treatments considered in this project. In the table, the initial installation costs were further added with a 20% contingency and 25% Construction Engineering and Inspection (CEI) costs that are typically cost items included in projects performed by contractors. Note that these cost estimates did not include costs due to traffic control, travel delays, and environmental impacts. In addition, the cost estimates did not include other potential cost items that might be involved in installation projects based on site conditions such as site preparation.

Table B14. Summary of Unit Costs for Delineation Treatments (2020 Dollars)

Treatment	Initial Installation		Annual Maintenance	Unit	Life Cycle (year)
	Item Estimate	With Contingency and CEI			
Rumble strips - shoulder	$0.49	$0.71	-	ft	10
Rumble strips - centerline	$0.54	$0.78	-	ft	10
Type A Pavement Line Marking 4"	$0.08	$0.12	-	ft	1
Type A Pavement Line Marking 6"	$0.10	$0.15	-	ft	1
Type A Pavement Line Marking 8"	$0.21	$0.30	-	ft	1
Type A Pavement Line Marking 12"	$0.24	$0.35	-	ft	1
Type B Class I Pavement Line Marking 4"	$0.53	$0.77	-	ft	3
Type B Class I Pavement Line Marking 6"	$0.84	$1.22	-	ft	3
Type B Class I Pavement Line Marking 8"	$1.46	$2.12	-	ft	3
Type B Class I Pavement Line Marking 12"	$3.17	$4.60	-	ft	3
Type B Class II Pavement Line Marking 4"	$4.12	$5.97	-	ft	3
Type B Class II Pavement Line Marking 6"	$2.24	$3.25	-	ft	3
Type B Class II Pavement Line Marking 8"	$6.51	$9.44			3
Type B Class II Pavement Line Marking 12"	$13.69	$19.85	-	ft	3
Type B Class III Pavement Line Marking 4"	$4.62	$6.70	-	ft	3
Type B Class III Pavement Line Marking 6"	$10.50	$15.23	-	ft	3
Type B Class IV Pavement Line Marking 4"	$3.50	$5.08			6
Type B Class IV Pavement Line Marking 6"	$4.76	$6.90			6
Type B Class VI Pavement Line Marking 4"	$2.84	$4.12	-	ft	6
Type B Class VI Pavement Line Marking 6"	$3.38	$4.90	-	ft	6
Type B Class VI Pavement Line Marking 8"	$4.68	$6.79	-	ft	6
Type B Class VI Pavement Line Marking 12"	$7.73	$11.21	-	ft	6
On-pavement Curve Warning Marking	$1,082.66	$1,569.86	-	Each	3
PMD – flexible	$59.22	$85.87	-	Each	3
Chevron - standard	$290	$420.50	-	Each	10
Chevron - 36 x 48 (freeway use)	$358	$519.10	-	Each	10
Curve Warning Sign with Flashing Beacons	$3,904.71	$5,661.83	-	Each	5
Sequential Chevron Curve Warning System	$3,200	$4,640.00	-	Each	10
Snowplowable RMP - concrete pavement	$62.59	$90.76	$6.66 for freeways and $4.44 for others	Each	10
Snowplowable RMP - asphalt pavement	$30.65	$44.44	$6.66 for freeways and $4.44 for others	Each	10
Plastic Inlaid Markers on Asphalt Pavement	$39.82	$57.74	$37.61 for replacing per 3 years	Each	10
Safety Edge (both sides)	$4,118.4	$5,971.68	-	Mile	10

References for Appendix B

AASHTO. Crash Cost Estimates. Appendix 4A. In *Highway Safety Manual*, 1st Edition. American Association of State Highway and Transportation Officials, 2010.

BLS a. *Employment Cost Index Historical Listing – Volume III: Current Dollar, March 2001-March 2021*. U.S. Bureau of Labor Statistics, April 2021. https://www.bls.gov/web/eci/echistrynaics.pdf. Accessed 05/22/2021.

BLS b. *CPI for All Urban Consumers (CPI-U)*. U.S. Bureau of Labor Statistics. https://beta.bls.gov/dataViewer/view/timeseries/CUSR0000SA0;jsessionid=0C907976E53EE338EA8C77EE859268F8. Accessed 05/22/2021.

BLS. *Employment Cost Index Historical Listing – Volume III*. Bureau of Labor Statistics, United States Department of Labor, December 2019.

Bahar, G., Mollett, C., Persaud, B., Lyon, C., Smiley, A., Smahel, T., and McGee, H. *Safety Evaluation of Permanent Raised Pavement Markers*. NCHRP Report 518. National Cooperative Highway Research Program, 2004.

Brimley, B., Hawkins, H. G. Jr., Himes, S., McGee, H., and Gross, F. *Traffic Control Device Guidelines for Curves*. NCHRP 03-106 Project final report. April 2015. http://onlinepubs.trb.org/onlinepubs/nchrp/docs/NCHRP03-106_FR.pdf. Accessed 04/24/2020.

Ceifetz, A., Yassin, J., Andridge, P., Kwigizile, V., Oh, J., and Burdick, B. *Evaluating Road Delineation Practices in Michigan*. Final Report, Michigan Department of Transportation, March 2017.

Cottrell, B. H. Jr., and Hanson, R. A. *Determining the Effectiveness of Pavement Marking Materials*. Virginia Transportation research Council, February 2001.

CMF Clearinghouse. *Synthesis of Countermeasure Service Life and Crash Severity Costs User Guide*. Crash Modification Factors Clearinghouse. http://www.cmfclearinghouse.org/resources_servlifecrashcostguide.cfm. Accessed 01/22/2020.

FHWA. LED Raised Pavement Markers. Project Summary FHWA-SA-09-007. Federal Highway Administration, May 2009. https://safety.fhwa.dot.gov/intersection/conventional/unsignalized/tech_sum/fhwasa09007/fhwasa09007.pdf. Accessed 04/27/2020.

FHWA. *Manual on Uniform Traffic Control Devices*. Federal Highway Administration, May 2012.

FHWA. *National Highway Construction Cost Index (NHCCI) 2.0*. Federal Highway Administration, July 2018. https://www.fhwa.dot.gov/policy/otps/nhcci/pt1.cfm. Accessed 09/28/2018.

FHWA a. *National Highway Construction Cost Index (NHCCI)*. Federal Highway Administration. https://www.fhwa.dot.gov/policy/otps/nhcci/. Accessed 02/28/2020.

FHWA b. *Rumble Strips and Rumble Stripes – Frequently Asked Questions*. Federal Highway Administration. https://safety.fhwa.dot.gov/roadway_dept/pavement/rumble_strips/faqs.cfm. Accessed 02/25/2020.

Fontaine, M. D., and Gillespie, J. S. *Synthesis of Benefits and Costs of Alternative Lane Marking Strategies*. Report No. FHWA/VTRC 09-R24. Virginia Transportation Research Council, May 2009.

Gartner, N. H., Stamatiadis, C., and Srinivas, S. *Improved Highway Lane Reflectorized Markers*. University of Massachusetts Lowell, February 2016.

Graham, J. L., Richard, K. R., O'Laughlin, M. K., and Harwood, D. W. *Safety Evaluation of the Safety Edge Treatment*. Report No. FHWA-HRT-11-024. MRIGlobal, March 2011.

Harmon, T., Bahar, G., and Gross, F. *Crash Costs for Highway Safety Analysis*. Report No. FHWA-SA-17-017. VHB, January 2018.

Howard, C., Springer, M., and Sharif, Y. Pavement Marking Life Cycle Cost Analysis. Presentation on 04/02.2015. https://connect.ncdot.gov/resources/safety/Signing%20and%20Delineation%20Library/Pavement_Marking_Cost_Analysis.pdf. Accessed 03/05/2020.

ILDOT. *Highway Safety Improvement Program Draft User Manual – Benefit-Cost Tool*. Illinois Department of Transportation, January 2017. http://www.idot.illinois.gov/Assets/uploads/files/Transportation-System/Manuals-Guides-&-Handbooks/Safety/HSIP%20Benefit%20Cost%20Tool%20User%20Guide.pdf. Accessed 04/23/2020.

Jiang, Y. *The Effectiveness and Criteria for Placement of Raised Pavement Markers (Synthesis Study)*. Report No. FHWA/IN/JTRP-2006/6. Purdue University, October 2006.

KTC a. *Average Unit Bid Prices*. Kentucky Transportation Cabinet. https://transportation.ky.gov/Construction-Procurement/Pages/Average-Unit-Bid-Prices.aspx. Accessed 04/27/2021.

KTC b. *Special Note for Inlaid Pavement Markers*. Kentucky Transportation Cabinet, December 5, 2018. https://transportation.ky.gov/Highway-Design/Pavement%20Design/SN%20for%20Inlaid%20Pavement%20Markers%205Dec2018.pdf. Accessed 04/27/2021.

Kuchangi, S. P., Benz, R. J., Nelson, A. A., Voigt, A. P., Stevens, R. G., Wikander, J. P., and Theiss, L. *Guidance for Effective Use of Pylons for Lane Separation on Preferential Lanes and Freeway Ramps*. Report No. FHWA/TX -13/0-6643-1. Texas A&M Transportation Institute, May 2013.

Liu, X., Bullough, J., Tian, L., Jiang, S., and Jafari, M. *Evaluation of Raised Pavement Markers*. Final Report FHWA-NJ-2018-004. Rutgers, The State University of New Jersey, July 2018.

McGee, H. W., and Hanscom, F. R. *Low-Cost Treatments for Horizontal Curve Safety*. Report No. FHWA-SA-07-002. Federal Highway Administration, December 2006.

Miller, T. R. Benefit-Cost Analysis of Lane Marking. *Public Roads*, 57-1, 1993.

Montebello, D., and Schroeder, J. *Cost of Pavement Marking Materials*. SRF Consulting Group, Inc., Minneapolis, MN, March 2000.

Nguyen, V. Plastic Inlaid Markers Migration. Presentation during VDOT/VAA Asphalt Seminar, Fredericksburg, VA, March 10, 2020.

Patterson, K., and Fitch, J. *Evaluation and Comparison of Snow Plowable Raised Pavement Markings*. Report No. 2007-8. Vermont Agency of Transportation, July 2007.

Pike, A. M., and Bommanayakanahalli, B. Development of a Pavement Marking Life Cycle Cost Tool. *Transportation Research Record*, Vol. 2672(12), 2018, 148-157.

Srinivasan, R., Baek, J., Carter, D., Persaud, B., Lyon, C., Eccles, K., Gross, F., and Lefler, N. *Safety Evaluation of Improved Curve Delineation*. Report No. FHWA-HRT-09-045. Federal Highway Administration, September 2009.

US Inflation Calculator. *Consumer Price Index Data from 1913 to 2020*. US Inflation Calculator. https://www.usinflationcalculator.com/inflation/consumer-price-index-and-annual-percent-changes-from-1913-to-2008/. Accessed 09/28/2018.

VDOT a. Chapter 3: Signing and Pavement Marking Design Standards. In *VDOT Governance Document - Traffic Engineering Design Manual*. Location and Design Division, Virginia Department of Transportation. September 2014.

VDOT b. *2011 Virginia Supplement to the 2009 MUTCD – Revision 1*. Virginia Department of Transportation, January 2014.

VDOT a. Section 1300 – Traffic Control. *2016 Road and Bridge Standards*. Virginia Department of Transportation, October 2019.

VDOT b. *Virginia Department of Transportation Special Provision for Inlaid Pavement Markers*. SP704-000120-00. Virginia Department of Transportation, August 26, 2019.

VDOT. *2020 Road and Bridge Specifications*. Virginia Department of Transportation, 2020.

VDOT. Two-Year Statewide Averages. *Resource Information*. Virginia Department of Transportation. http://www.virginiadot.org/business/const/resource.asp. Last updated 4/5/2021.