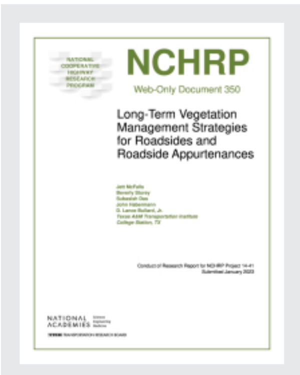
NCHRP
Web-Only Document 350
Long-Term Vegetation Management Strategies for Roadsides and Roadside Appurtenances

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NCHRP

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Long-Term Vegetation Management Strategies for Roadsides and Roadside Appurtenances

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Conduct of Research Report for NCHRP Project 14-41
Submitted January 2023

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed, and implementable research is the most effective way to solve many problems facing state departments of transportation (DOTs) administrators and engineers. Often, highway problems are of local or regional interest and can best be studied by state DOTs individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation results in increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

Recognizing this need, the leadership of the American Association of State Highway and Transportation Officials (AASHTO) in 1962 initiated an objective national highway research program using modern scientific techniques—the National Cooperative Highway Research Program (NCHRP). NCHRP is supported on a continuing basis by funds from participating member states of AASHTO and receives the full cooperation and support of the Federal Highway Administration (FHWA), United States Department of Transportation, under Agreement No. 693JJ31950003.

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C O O P E R A T I V E R E S E A R C H P R O G R A M S

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FOREWORD

Ann Hartell

NCHRP Web-Only Document 350 presents information on strategies that control the establishment and growth of roadside vegetation over an extended period, reducing the need for herbicides, mowing, and other mechanical controls. The report and accompanying resources will be of interest to those responsible for designing and maintaining the roadside environment.

Control of vegetation along roadsides is required for fire prevention, adequate sight distance, facility inspection needs, reduction of invasive and nuisance weeds, roadside aesthetics, and protection of roadside appurtenances, such as guardrails, cable barriers, and sign posts. Roadside vegetation can be controlled using herbicides, mowers, and other equipment or, alternatively, by strategies designed to prevent or significantly retard the growth of unwanted vegetation for longer periods. These long-term vegetation management strategies include asphalt or concrete surface treatments, mats, mulches, or competitive vegetation.

Long-term vegetation management strategies that decrease the need for routine chemical and mechanical vegetation control can reduce recurring maintenance costs, highway worker exposure to traffic, impacts to the environment and cultural resources, and maintenance-related delays to the traveling public. However, these strategies vary in their effectiveness, longevity, initial construction costs, maintenance requirements, and aesthetic values. A critical consideration is how any strategy may affect the safety performance of highway appurtenances, such as guardrails, cable barriers, and sign posts. This is because surface and soil conditions are part of the design of roadside safety appurtenances, so designers need to understand any potential interactions between design elements that can affect safety performance.

The American Association of State Highway and Transportation Officials (AASHTO) Guidelines for Vegetation Management, published in 2011, collected and compiled information about roadside vegetation management. However, information on long-term strategies was limited and did not fully address how these design elements can interact with some common roadside appurtenances, such as cable barriers. Furthermore, recent field research and on-going experience from state department of transportation (DOTs) offers new insights into installation requirements, costs, effectiveness, and aesthetics.

NCHRP Web-Only Document 350 provides up-to-date information on long-term vegetation management strategies for new construction and retrofits to existing facilities in a range of contexts. The report and accompanying materials describe a range of strategies along with information about effectiveness, relative costs, aesthetics, and longevity. Because safety—for motorists, construction workers, and maintenance crews—is an imperative for roadside design, the report includes information on potential interactions between vegetation management strategies and roadside appurtenances as well as construction and maintenance requirements that affect worker exposure to traffic.

The research was conducted by Texas A&M Transportation Institute (TTI). The research effort included a review of relevant research and design guidelines along with a survey of practitioners. The report is accompanied by a downloadable interactive tool for selecting vegetation management strategies based on critical inputs about the location. Also available is a tabular presentation with 20 strategies and key considerations for each, designed for quick, desktop reference. A set of presentation slides with speaker notes summarizes the project. These materials are available on the TRB website and can be found by searching for “NCHRP Web-Only Document 350”.

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SUMMARY

Finding effective and economical non-herbicide, long-term vegetation management strategies (VMSs) to reduce the need for recurring chemical and mechanical vegetation controls has been a challenge for departments of transportation (DOTs). Vegetation management at key roadside locations and roadside appurtenances involves the safety of the traveling public and maintenance personnel, environmental impacts, roadside aesthetics, and budget constraints.

Data were compiled through a survey of practice and a review of relevant research and DOT documents and websites. The research focused on VMS issues such as effectiveness, longevity, initial construction costs, maintenance costs and requirements, safety, interaction with highway appurtenances, and aesthetic values. Researchers identified typical materials and VMS usage locations. The use of VMSs improves both worker and driver safety by minimizing worker exposure on the roadsides for recurring maintenance and reducing traffic diversions and delays for maintenance activities. The safety of maintenance personnel is directly related to the level of difficulty and/or time requirements for material installation, maintenance, and repair. Workers' safety is greatly affected by increased exposure to traffic and other roadside hazards. The need for prolonged traffic controls necessary to complete the required tasks is an important consideration. Therefore, each VMS receives a level of difficulty rating of low, moderate, or high. This is not only indicative of the specific VMS material characteristics but also includes the relative level of worker safety and exposure during installation, maintenance, and repair.

The VMS locations examined in this study include cable barriers, support posts and poles, edge of pavement, gore/median, guardrail, mow edge/strip, and slope/embankment. The VMS has three basic categories: impervious surfaces, pervious surfaces, and select vegetation establishment. VMSs are designed to cover the designated area and minimize maintenance activities, particularly adjacent to the travel lanes.

VMSs applied in and around highway safety appurtenances should be done so cognizant of their effect on the performance of everything in the highway design environment. If a VMS is thought to possibly have a performance effect on a highway safety appurtenance, then consideration should be given to crash testing the VMS and safety appurtenance together as a system. As of January 1, 2011, all newly developed hardware must be tested using the *Manual for Assessing Safety Hardware* (MASH). Of particular interest to the application of VMSs, the Federal Highway Administration (FHWA) also issued a memorandum dated January 7, 2016, regarding the federal-aid eligibility of highway safety hardware after December 31, 2016. The following applies to VMSs:

- FHWA will no longer issue eligibility letters for highway safety hardware that has not been successfully crash tested to the 2016 edition of MASH.
- Modifications of eligible highway safety hardware must use criteria in the 2016 edition of MASH for reevaluation and/or retesting.
- Non-significant modifications of eligible hardware that have a positive or inconsequential effect on safety performance may continue to be evaluated using finite element analysis.

Cost and worker safety are key issues for DOTs. Material choice needs to consider a broad range of issues that weigh material and installation costs versus maintenance worker exposure in high-traffic areas. Some VMSs may have a low initial cost but are labor intensive to install and maintain. Another consideration is the environmental impact of various VMSs. In environmentally sensitive areas where herbicide use is unacceptable, highly effective VMSs are a key decision factor over material and installation costs.

Researchers used a web-based survey sent to all state DOT maintenance directors requesting information on current practices, institutional obstacles, and the concerns that DOTs have regarding VMS usage. Requested information included the DOT selection process for VMSs, innovative methods or technologies, and information on any additional guidance that is required. Seventeen states responded to the survey, with some states giving multiple responses based on regional differences.

Survey results showed the most common VMS locations are at guardrails, cable barriers, and the edge of pavement. The most used VMSs reported by the respondents are minor concrete pavement, asphalt, gravel, and native and non-irrigation vegetation. Researchers found difficulty in gathering information because VMSs are often not specified as such. They are part of a greater design/construction element. For example, placing concrete under guardrail is part of many guardrail construction manuals and/or specifications. However, concrete at similar locations is generally not labeled as a VMS.

Researchers were tasked with developing an Interactive Selection Tool to provide information on non-herbicide, long-term VMSs for roadsides and roadside appurtenances that are appropriate for new and retrofit construction. The development of the Interactive Selection Tool was based on the information collected from the literature review, survey of practice, and follow-up interviews with select DOTs. Twenty VMSs were identified for inclusion in the tool (see Chapter 5 and Appendix C for details on each VMS).

There is a growing body of research and project implementation regarding the use of VMSs. While there are emerging products within the industry, few studies have been conducted on product performance as it relates to non-herbicide, long-term VMSs. However, for many DOTs, implementation and/or demonstration projects using new techniques and/or products are conducted internally and may not be made publicly available through typical website searches.

This project was also tasked with identifying knowledge gaps and possible updates/additions to the American Association of State Highway and Transportation Officials *Guidelines for Vegetation Management*. The following sections describe this task.

RESILIENCE

Transportation resilience is the ability of a transportation system to function at an acceptable rate in the event of extreme weather events, major crashes, and equipment or infrastructure failures. Quick recovery of a system is critical to avoid long-term effects. State DOTs need information on VMSs that can increase the resilience of transportation facilities and the transportation system.

POLLINATORS

In June 2014, the White House issued the Presidential Memorandum (PM), "Creating a Federal Strategy to Promote the Health of Honeybees and Other Pollinators." The PM directs federal agencies to take additional steps to improve habitat for pollinators, including honeybees, native bees, birds, bats, and butterflies—critical contributors to our nation's economy, food system, and environmental health. With millions of acres of highway roadsides, state and local transportation agencies own or control land with the ability to conserve and/or create important habitat corridors that link otherwise fragmented pollinator habitat. State DOTs need information on how to update their vegetation management policies, practices, and standards to align with the PM on pollinators.

HERBICIDES

Herbicide-resistant weeds are becoming problematic for roadside vegetation managers. Herbicide manufacturers are changing the basic chemistry to combat resistance. This is becoming more and more difficult as some chemicals are being deleted from the roadside maintenance arsenal. The U.S. Department of Agriculture has taken over all aspects of herbicide control (i.e., licensing, training, etc.). State DOTs need information on how to respond to herbicide resistance and the current regulatory environment.

MANAGED SUCCESSION

Many DOTs are implementing more non-mow or reduced-mow areas within their rights of way due to the cost, safety, and environmental benefits of managed succession of roadside vegetation outside the safety clear zone. Many of the benefits fall under ecosystem services (ESs). These ES benefits include ecosystem diversity, stormwater quantity and quality management, carbon sequestration, erosion control, pollinator corridor development, wildlife habitat, and aesthetics.

State DOTs need information on how managed succession can be used to advance environmental benefits, deliver ESs, and better manage roadside vegetation.

CHAPTER 1. INTRODUCTION

DOTs have historically incorporated a range of roadside vegetation management techniques within the right of way (ROW) to maintain adequate sight distance, reduce invasive and nuisance weeds, provide roadside aesthetics, and protect roadway infrastructure and roadside appurtenances. Many of these techniques are often included as part of the respective agency's Integrated Vegetation Management Plan. The most used methods for vegetation control include mowing and other mechanical removal techniques, and chemical treatments such as herbicides. The American Association of State Highway and Transportation Officials (AASHTO) published *Guidelines for Vegetation Management* in 2011 to assist DOTs with their vegetation management programs (AASHTO 2011a). Specifically, DOTs seek more effective and economical **non-herbicide, long-term VMSs** to reduce the need for recurring chemical and mechanical vegetation controls. This action may help DOTs reduce maintenance costs, safety hazards for roadway users and maintenance personnel, exposure to herbicides, environmental and cultural impacts, and maintenance-related delays to the traveling public.

Transportation agencies generally categorize their roadside management strategies according to the different management zones. Figure 1 shows the respective roadside zones. Zone 1 is considered the operational zone, and its management includes pavement preservation, erosion control, safety-related issues such as sight distance, and maintenance of roadside appurtenances and signs. Zone 1 is the main area of concern for this project and is often a vegetation-free zone. However, VMSs are also used along roadsides, in medians and gores, and in other areas with appurtenances such as cable barrier systems requiring control measures to ensure that infrastructure has minimal maintenance requirements.

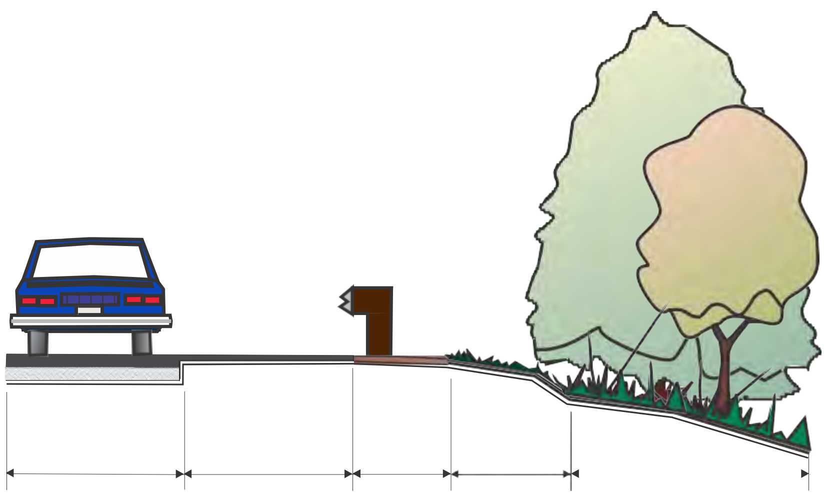

Figure 1. Roadside Management Zones (Adapted from Washington State Department of Transportation 2015).

The importance of managing unwanted vegetation in Zone 1 and those areas containing barriers, support posts and poles, and other appurtenances lies in the safety risks for maintenance personnel and the potential damage caused by unwanted vegetative growth. Maintenance personnel's safety is greatly affected by increased exposure to traffic and other roadside hazards. Unwanted vegetation at the edge of pavement can cause a buildup of litter, debris, sand (from winter operations), and sediment that impedes stormwater runoff from leaving the roadway and provides fuel for roadside fires.

RESEARCH APPROACH

The goal of the research conducted for National Cooperative Highway Research Program (NCHRP) Project 14-41 is to produce up-to-date and user-friendly guidance for transportation agencies to facilitate the selection of appropriate non-herbicide, long-term VMSs that will be effective in preventing or significantly retarding the growth of unwanted vegetation around roadside appurtenances and along roadsides.

The project goal was accomplished through two objectives. The first objective was to conduct a thorough assessment of VMS usage and practices in the United States. This assessment included relevant research regarding effectiveness, longevity, initial construction costs, maintenance requirements, safety performance of highway appurtenances, and aesthetic values. Researchers gathered information on VMS usage through a detailed review of the literature, targeted interviews with technical experts, a web-based survey of transportation practitioners, and in-depth interviews with practitioners that have piloted or implemented additional methods, technologies, or applications.

The second objective was to develop an interactive tool to assist agencies in the selection of an appropriate VMS. The Interactive Selection Tool will help agencies evaluate the potential costs and benefits of each VMS for a given scenario. The development of the tool was based on the information collected from the literature review, a survey of practice, and follow-up interviews with select DOTs. This tool employs a decision algorithm to advise the user of an appropriate VMS treatment for the specific conditions. The tool can be downloaded and used in a self-contained folder format. Chapter 5 provides more information, and Appendix B provides the user manual and instructions for downloading and extracting the files.

RESEARCH METHODOLOGY

The research approach for this project included a detailed literature review, a review of state transportation agency VMS practices, and a survey of practice with select follow-up interviews. The identification and development of guidance material involved the following five tasks:

- **Task 1: Project Management.** The objectives of this task were to ensure that the research was conducted as defined in the detailed work plan within the agreed-upon time and resources and to effectively communicate with the NCHRP technical representative regarding the direction of the project along with progress updates.

- **Task 2: Conduct Literature Review.** This task objective was to document the state of the practice through a review of online documents and to review the literature on the effectiveness, longevity, initial construction costs, maintenance requirements, site conditions, ecological and climate conditions, and aesthetic value of VMS treatments and their effect on the safety performance of highway appurtenances, such as guardrails, cable barriers, and signs.

- **Task 3: Conduct Web-Based Survey and Practitioner Interviews.** The objective of this task was to supplement the information gathered in Task 2. Specifically, the research team aimed to collect information on current practices, institutional obstacles, issues, and concerns agencies have regarding VMS treatments. The research team also identified additional methods and technologies that DOTs are piloting or experimenting with, additional guidance required, and how DOTs can use the findings from this research.

- **Task 4: Develop Interactive Selection Tool.** The objective of Task 4 was to develop the Interactive Selection Tool to provide step-by-step guidelines for transportation agencies to identify and select non-herbicide VMSs. The development of the Interactive Selection Tool was informed by and based on the information collected in Tasks 2 and 3.

- **Task 5: Prepare Final Deliverables**. The objective of this task was to prepare the final project documentation, which includes this report documenting the research, the Interactive Selection Tool, and a graphic presentation of long-term non-herbicide VMSs.

TERMINOLOGY

Researchers found many common terms applied in the topic area of non-herbicide, long-term VMSs, roadsides, and roadside appurtenances. Table 1 defines these terms for use throughout the remainder of this report.

Table 1. Terminology Related to VMSs.

Term	Definition
Guardrail	"A guardrail is a safety barrier intended to shield a motorist who has left the roadway. Guardrails can make roads safer and lessen the severity of crashes. The guardrail can operate to deflect a vehicle back to the roadway, slow the vehicle down to a complete stop, or, in certain circumstances, slow the vehicle down and then let it proceed past the guardrail" (FHWA n.d.).
Strong post guardrail	"The most widely used barrier—the strong post W-beam guardrail identified as SGR-04 in the *Standardized Highway Barrier Hardware Guide* (TF 13). (The term guardrail, and in some states guiderail, is commonly used either for just W-beam barriers or for barriers in general; for future use in this guide, the term W-beam guardrail will refer to the strong post W-beam barrier system.) The standard strong post W-beam guardrail consists of a W-beam rail element and strong posts (wood or steel) spaced at 6 ft 3 in with the rail blocked out from the posts." The wood post is typically a nominal 6 inches by 8 inches by 72 inches, and the steel post is W6x8.5 or W6x9 and 72 inches long. The W-beam is typically 12 gauge (Fitzgerald 2008).
Cable barrier	Includes median and roadside cable barrier systems. "Cable barriers are softer, resulting in less impact force and redirection, are more adaptable to slopes typically found in medians, and can be installed through less invasive construction methods" (FHWA 2022). Cable barriers typically have higher deflections when impacted than guardrail. Cable barrier installations can vary in the number of cables and post spacing used. More cables and closer post spacing will result in a smaller deflection and higher impact forces when struck.

Support posts and poles	Any post or roadside appurtenance such as signs, luminaire supports and poles, lights, outdoor advertising, etc. requiring a VMS treatment at the base.
Edge of pavement	The interface where the roadway edge meets the adjacent material.
Gore/median	A gore area is located where roads merge or split. A median is the area separating opposing traffic lanes. These two categories are grouped due to similar characteristics for choosing a VMS.
Mow edge/strip	A VMS strip placed at the edge of a noise wall, roadside appurtenance, etc. that facilitates mowing. The terms *edge* and *strip* are often used interchangeably.
Slope/embankment	Areas where the roadside rises or falls from the roadway elevation. The degree of steepness is site specific.

CHAPTER 2. LITERATURE REVIEW

Finding solutions for non-herbicide VMSs has been a challenge for transportation agencies. The management of vegetation at key locations such as guardrails, cable barriers, luminaire supports and poles, and other roadside appurtenances involves the safety of the traveling public and maintenance personnel, environmental impacts, roadside aesthetics, and budget constraints. A review of the available literature and an internet search gathered data regarding the usage of VMSs. This chapter covers research and DOT practices regarding the use of VMSs as designated by the project.

The information presented provides identification and guidance for the selection of non-herbicide, long-term VMSs for roadsides and roadside appurtenances. The VMSs identified and presented do not present specific design guidance for highway safety appurtenances, nor are they a substitute for any other highway design practice. The user should refer to the AASHTO *Roadside Design Guide* (RDG), AASHTO MASH, and any specific state DOT practices for warrants, proper placement, and maintenance of roadside safety appurtenances when applying these VMSs (AASHTO 2011b, 2016). In addition, before applying any of the techniques described on a proprietary roadside safety hardware device (e.g., guardrail terminal, crash cushion, or breakaway sign support), the manufacturer should be contacted to discuss the potential for the treatment to adversely affect the performance of the manufacturer's safety hardware device.

The project team reviewed the 2011 AASHTO *Guidelines for Vegetation Management* (AASHTO 2011a), which lists numerous VMSs. Each has advantages and disadvantages for roadside and median applications. Much of the information contained in Chapter 12 of the AASHTO *Guidelines for Vegetation Management* came from the California Department of Transportation's (Caltrans's) comprehensive website called the Roadside Management Toolbox. The current version of the Roadside Management Toolbox can be accessed on the Caltrans website (Caltrans 2017a).

As a general statement, all VMSs are subject to surface accumulation of soil, seeds, and debris and may require spot treatments to control unwanted vegetation and debris removal. Textured surfaces may allow for more accumulation. However, the use of VMSs significantly reduces the need for recurring maintenance activities and herbicide treatments. The use of VMSs improves both worker and driver safety by minimizing worker exposure on the roadsides for recurring maintenance and by reducing traffic diversions and delays for maintenance activities. The VMS locations examined in this study and defined in Table 1 are:

- Guardrail
- Cable barrier
- Support posts and poles
- Edge of pavement
- Gore/median
- Mow edge/strip
- Slope/embankment

The VMSs have three basic categories that include impervious surfaces, pervious surfaces, and select vegetation establishment. VMSs are designed to cover the designated area and minimize maintenance activities, particularly adjacent to the travel lanes. Impervious surface VMSs are enduring and very effective but can be more expensive to install. Potential problem areas associated with impervious materials used as a VMS (i.e., concrete, asphalt, and others) are the leave-out areas or post deflection spaces around posts and other fixed objects in proximity to or around roadway safety devices that may accumulate unwanted vegetation. Nonetheless, leave-outs may be required for some VMS use locations due to the effect that the rigidity of the VMS material may have on altering the performance when placed around roadway safety devices.

Pervious surface VMSs allow for stormwater runoff infiltration. Pervious surface VMSs are designed to block sunlight to inhibit plant growth. Some pervious surface VMSs may use a geosynthetic fabric (herbicide or non-herbicide treated) to inhibit root growth placed underneath the VMS. Several of the pervious VMS choices are advantageous for retrofit applications.

The third category involves the establishment of specific plant material in designated areas. The vegetation used around roadside appurtenances should have a low mature height, require minimal maintenance, and be able to out-compete weed growth. This vegetation can be native or non-native and irrigated or non-irrigated depending on the site-specific requirements.

VMSS AND PERFORMANCE OF HIGHWAY SAFETY APPURTENANCES

Highway safety appurtenances reduce the severity of an errant motorist leaving the roadway. Many features of the roadway and roadside influence the ability of the safety device to perform properly. These features may include but are not limited to the slopes and ditches parallel to the roadside; discontinuities in the travel surface; the presence of other fixed objects; safety devices within the clear zone such as signs, luminaires, delineators, curbs, and sidewalks; and soil moisture. In addition, the geometric alignment of the roadway can affect the performance of safety devices located off and along the roadway. The roadway and roadside are an operating environment, and their performance has a symbiotic relationship with their features. The designer should always be cognizant of the effect that changes may have on the function of each of the individual components within the roadway environment.

In addition, before applying any of the VMS techniques described herein to a proprietary roadside safety hardware device (e.g., guardrail terminal, crash cushion, or breakaway sign support), the manufacturer should be contacted to discuss if and how the treatment might adversely affect the performance of the manufacturer’s safety hardware device. The effects that VMSs could potentially have on the performance of roadside safety appurtenances are presented in the following sections. Appendix E provides more information regarding roadside safety.

Roadside safety hardware design continues to evolve, and the testing of safety systems is an active area of research. Designers must stay abreast of the research and published MASH Tests to evaluate the safety performance of any configuration of roadside safety appurtenances and VMSs.

MASH provides the following five categories or classes of highway safety appurtenances:

1. Longitudinal barriers
2. Terminals and crash cushions
3. Truck- and trailer-mounted attenuators and portable work zone traffic control trailers
4. Support structures, work zone traffic control devices, breakaway utility poles, and longitudinal channelizers
5. Roadside geometric features and pavement discontinuities

Longitudinal Barriers

Longitudinal barriers include roadside, median and temporary barriers, and bridge rails and transitions. Longitudinal barriers are all designed to contain, shield, or redirect an errant vehicle from a roadside hazard. Longitudinal barriers may be additionally divided into categories of rigid, semi-rigid, and flexible that are based on the stiffness/deflection characteristics when impacted. When barriers of different stiffness are joined, they are connected via a transition section of barrier. Transitions are commonly found where, for example, a rigid concrete bridge rail is joined to a semi-rigid W-beam guardrail.

The performance of longitudinal barriers depends on their specific design features. All longitudinal barriers are designed for engagement of the errant vehicle within specific vehicle center-of-gravity (CG), weight, and impact angle envelopes along the barrier's height profile. For example, a concrete safety shape barrier has a specific geometric profile that interacts with the bumper and CG of the vehicle. Any change in the height at which the vehicle engages the barrier could alter the barrier's ability to safely redirect an impacting vehicle. A VMS should not alter the acceptable construction height tolerances of the barrier or eliminate or modify a feature of the geometric profile of the barrier (e.g., eliminate the toe of a concrete barrier or raise or lower a rail height), thus raising or lowering the vehicle impact point or the way an errant vehicle engages the barrier.

Rigid and semi-rigid barrier performance depends on the structural stiffness and lateral displacement characteristics to perform properly. A rigid barrier does not experience lateral displacement during impact and should remain rigidly affixed to its foundation and the roadway surface. Rigid barriers are typically concrete barriers (e.g., concrete safety shape and vertical concrete wall). Use of VMSs around such barriers is acceptable provided the treatment does not extend above the pavement surface and does not alter the height of the barrier.

Converse to the rigid barrier, the semi-rigid barrier does displace and rotate when impacted, and those specific characteristics should also not be changed. Examples of semi-rigid barriers are portable concrete barriers of various lengths and connection types and W-beam and thrie beam guardrail. The semi-rigid portable concrete barriers may be installed in temporary or permanent applications. Their performance is specific to the length of the barrier and the connection between barrier segments. The displacement and rotation characteristics of the semi-rigid concrete barrier are unique to the specific design configuration. A VMS applied to a portable semi-rigid concrete barrier should not alter the barrier installation's ability to displace laterally or rotate upon impact. Any VMS treatment should be passive in nature with regard to weight and anchorage and not add to or subtract from the original design anchorage and connection performance for portable semi-rigid concrete barriers. Additionally, the designer should be cognizant of potential effects between a VMS that is placed on the non-traffic side of the barrier and any other safety feature that is installed behind the barrier. For example, pavers placed between a barrier and a signpost will have some mass and/or rigidity that can be displaced by an errant vehicle impact. The pavers can potentially restrain the movement of the barrier, affecting its safety performance, and/or can be displaced into a slip base sign support, activating the sign support.

Metal beam guardrail/guard fence (e.g., W-beam and thrie beam) can be configured as a semi-rigid or flexible longitudinal barrier. Within this category of metal beam longitudinal barriers, the rail element may be supported by either strong posts (e.g., W6x8.5 or W6x9) to provide a semi-rigid barrier or weak posts (S3x5.7) to provide a flexible barrier. In MASH strong post W-beam or thrie beam installations, the posts are typically steel W6x8.5 or W6x9 posts that are augured and backfilled or driven into the soil. The proper lateral displacement and rotation of the posts reduce the chances of rail rupture and are critical to the proper operation of the barrier when impacted. The AASHTO RDG and FHWA eligibility letters provide information about VMSs, such as mow strips, rock formations, and other rigid structures that are acceptable for use with these barriers. Additional information from the AASHTO RDG regarding strong post installation in mow strips and similar installations is presented hereafter.

Mow edges, also referred to as mow strips by AASHTO, prevent vegetation growth several feet around guardrail installations, including cable barriers, W-beam guardrail, guardrail transitions, and guardrail end treatments. W-beam guardrail posts, guardrail transition posts, and guardrail end treatment posts are treated equally with regard to the application of VMSs. However, a VMS should not be applied to any proprietary guardrail end treatment without first consulting with the product manufacturer. Mow strips are typically asphaltic or concrete pavement and vary in thickness from several inches up to 200 mm (8 inches) maximum. Strong post W-beam guardrail posts in mow strips and rock formations face similar problems regarding facilitating rotation of the strong posts.

The AASHTO RDG provides guidance regarding the use of mow strips and posts in rock for strong post W-beam guardrail systems. This information is based on research and crash testing conducted under NCHRP Report 350 (Ross et al. 1993). More recent research and full-scale MASH testing have been conducted for strong post W-beam guardrail in mow strips with leave-outs, the portion of the mow strip omitted around the base of the post to allow for post rotation. The 31-inch W-beam guardrail system with steel posts in a concrete mow strip performed acceptably for both MASH Tests 3-10 and 3-11, and therefore the steel post W-beam system in a concrete mow strip is considered acceptable for MASH Test Level 3 (TL-3) longitudinal barrier (Sheikh et al. 2019). In this design, the critical measurement of the leave-out installation is from the back of the post to the edge of the mow strip; this measurement should be a minimum of 175 mm (7 inches). Wood post W-beam guardrail did not meet MASH TL-3 safety requirements in all cases. Standard strong post guardrail with 6-inch by 8-inch rectangular wood posts and 7½-inch-diameter round wood posts embedded 40 inches both failed to meet the MASH TL-3 criteria when installed in mow strips with leave-outs (Sheikh et al. 2019, Bligh et al. 2020). However, a modified 7½-inch-diameter round wood post system with 36-inch embedment (Moran et al. 2020) was full-scale crash tested by the Texas Department of Transportation (TxDOT) in a mow strip with leave-outs and did meet MASH TL-3 safety requirements. A 6-inch by 8-inch rectangular wood post system with 35-inch embedment also met MASH TL-3 criteria (Moran et al. 2021). These recent findings suggest that leave-outs remain a viable method for use in mow strips with both steel and wood post W-beam guardrail systems. Wood post W-beam guardrail systems appear to be more sensitive to the use of mow strips, and care should be taken to ensure the proper post configuration and embedment depth.

As previously discussed, MASH testing is an active area of research, and design evolution is occurring. As a result, the RDG is out of date for some applications. Designers should always check that a mow strip design has been evaluated in accordance with MASH. For illustrative purposes, Figure 2 shows the details from Figures 5-52(a) and 5-52(b) of the AASHTO RDG (AASHTO 2011b). Leave-outs can be filled with low-strength grout, two-part polyethylene foam, or other material that has a compressive strength of 0.85 MPa (120 psi) or less. During an impact, the leave-out material allows for some degree of post rotation by deforming or crushing prior to generating sufficient force to cause post failure. Failure of the sacrificial leave-out backfill material also minimizes damage to the surrounding mow strip.

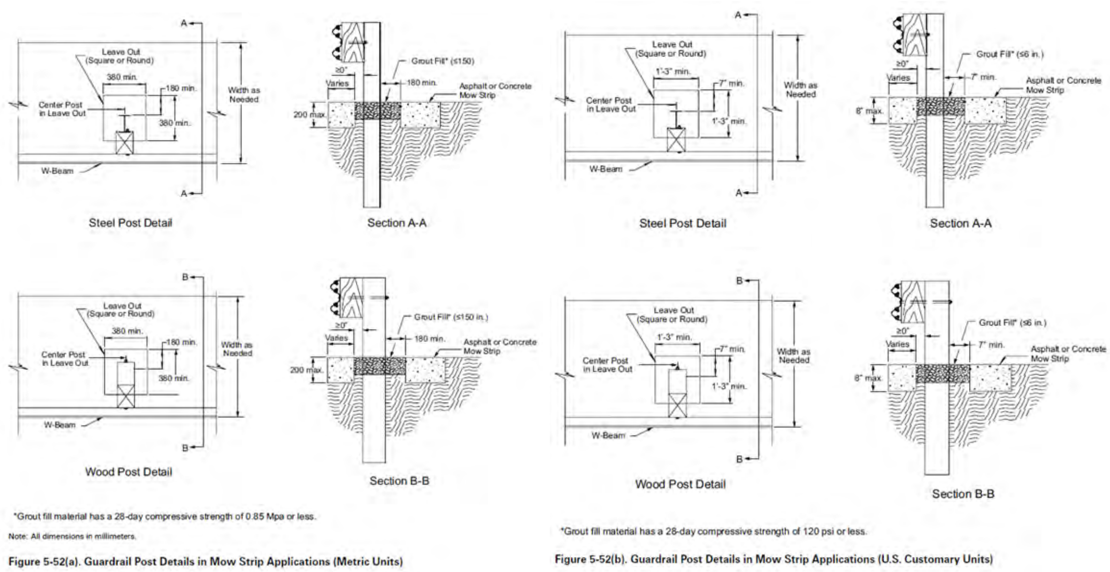

Figure 2. AASHTO RDG Guardrail Post Detail in Mow Strip Application (AASHTO 2011b).

Posts in high-tension cable barriers and other weak post (e.g., S3x5.7 steel post) guardrail systems do not need a leave-out in the mow strip. Weak post barrier systems do not rely on the displacement and rotation of the post, like a strong post system does, to perform successfully. During an impact, weak posts bend at or near the groundline and thus may be more rigidly constrained by the applied VMS.

For strong steel post W-beam guardrail posts installed in asphalt or concrete surfacing that is thicker than 200 mm (8 inches), Figure 3 shows AASHTO RDG Figures 5-5l (a) and 5-5l (b) for installation in rock formations (AASHTO 2011b). For these installations, the backfill around the posts is typically a coarse aggregate material. In some locations, it may be beneficial to seal the surface with an asphaltic crack sealant or other similar material to reduce water infiltration.

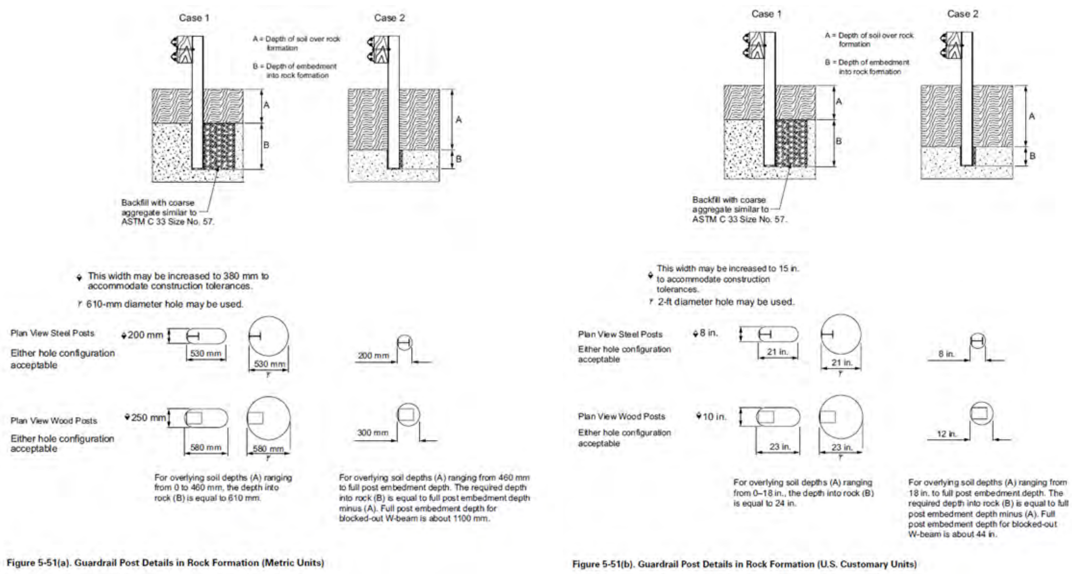

Figure 3. Guardrail Post Details in Rock Formation (AASHTO 2011b).

A strong steel post W-beam guardrail system installed in simulated rocky terrain following the guidance provided in Figure 3 was successfully tested to MASH TL-3 (Bligh et al. 2019). A round wood post W-beam guardrail system tested in a similar configuration did not satisfy MASH criteria (Bligh et al. 2019).

Terminals and Crash Cushions

Terminals and crash cushions both serve similar functions, which is to reduce the severity of a motorist impacting the terminus of a longitudinal barrier, bridge pier, gore area, or other rigid or semi-rigid structure. Terminals shield the end of a longitudinal barrier and reduce the impact severity of an errant vehicle striking the end of the barrier by absorbing the kinetic energy of the vehicle, permitting the vehicle to gate behind the barrier, or redirecting the vehicle if the barrier is struck along its side. Likewise, crash cushions perform in much the same way by attenuating the crash energy of the impact. However, not all crash cushions are re-directive if impacted along their side.

MASH-tested terminals and crash cushions are all proprietary to date. As previously presented, before applying any of the VMS techniques described herein to a proprietary roadside safety hardware device (e.g., guardrail terminal, crash cushion, or breakaway sign support), the manufacturer should be contacted to discuss if and how the treatment might adversely affect the performance of the manufacturer’s safety hardware device. VMS treatment may be applied to the area leading to and around the safety device to the extent the treatment does not create discontinuities or a change in elevation in or around the approach and departure areas of the device. Much like longitudinal barriers, crash cushions and terminals are designed and tested for engagement of an errant vehicle within specific vehicle CG, weight, and impact angle envelopes along the safety device’s height profile. Curbs and VMS treatments that create lift or upset the vehicle and its suspension when struck should not be introduced in and around these devices unless crash tested and accepted for use in the tested (as-implemented) configuration.

Truck- and Trailer-Mounted Attenuators and Portable Work Zone Traffic Control Trailers

Truck- and trailer-mounted attenuators (TMAs) and work zone traffic control trailers are portable devices that are normally deployed in temporary applications. TMAs are used to shield stationary or slow-moving trucks that are used in maintenance and work zones. Portable work zone traffic control trailers are also used in maintenance and work zones and commonly parked along the roadside. Work zone trailers are normally equipped with variable message signs and arrow boards. These devices will not be addressed with regard to the application of VMSs because they are portable and mobile in nature and are moved either continuously or frequently.

Support Structures, Work Zone Traffic Control Devices, Breakaway Utility Poles, and Longitudinal Channelizers

Support structures include sign supports, luminaire supports, emergency call box supports, and road closure gates. These supports, along with work zone traffic control devices and breakaway utility poles, all use some form of a vertical structural support that poses a potential hazard if an errant vehicle impacts it. Additionally, these devices commonly use a breakaway feature (e.g., slip base) or are fabricated of a frangible or yielding material that permits the support structure to yield, displace, or be frangible (e.g., frangible cast aluminum luminaire base) when impacted and thus reduce the severity of a vehicle impact. The AASHTO RDG provides examples of these types of breakaway devices. Figures 4, 5, and 6 from the AASHTO RDG show examples of a small sign support slip base, a frangible aluminum luminaire base, and a luminaire attached to a frangible coupling base, respectively. As the figures show, all the foundations in these examples are rigidly anchored to the ground and are designed not to move to facilitate activation of their safety feature.

The term *breakaway* refers to all supports that are designed to incorporate a feature that permits it to yield, fracture, or separate from its ground anchor or foundation when impacted by a vehicle. When an impact to a support occurs by an errant vehicle, the support and what is attached to the support such as a sign panel or luminaire, for example, should yield to the vehicle. Depending on the design, the vehicle will either pass over the installation, or the system will release and separate from its foundation and rotate over the vehicle without causing excessive deformation or intrusion into the occupant compartment. The support and its attachments rotating over the vehicle should make as little, if any, contact as possible with the windshield and roof. The weight of the support, the features attached to the support, and the location where they attach vertically and horizontally on the support all play a vital role in the proper operation of the safety device when impacted. Therefore, any modifications to the safety device can alter its performance. When a VMS is applied to one of these devices, it is necessary that the treatment does not infringe on the operation of the device when impacted. In the case of a slip-base-type sign support (Figure 4), the applied VMS must not interfere with the ability of the support to displace the bolts clamping the support to the ground stub anchor plate or interfere with the ability of the support to rotate away from the ground stub anchor plate when impacted.

Figure 4. Multidirectional Slip Base for Small Signs (AASHTO 2011b).

If a luminaire base is being evaluated for use with a VMS, the designer should be cognizant of not changing the interaction height between the errant vehicle and the frangible base or couplings. This statement also applies to slip base supports. Slip base, cast aluminum frangible luminaire base (Figure 5), and other types of breakaway sign support systems (Figure 6) may be sensitive to the impact height of the vehicle bumper. The typical automobile bumper height is approximately 51 mm (20 inches). Slip base supports are designed to activate in shear and not in bending stress. Slip base supports and other breakaway safety devices may not activate properly if the impacting height of the vehicle is affected by design elements such as super-elevation, slopes, and ditches. Foreslopes of 1V:10H or flatter between the roadway and the support help ensure consistent approach conditions and vehicle interaction height. The acceptable foreslope is limited to 1V:6H or flatter between the roadway and the support if the vehicle bumper height can interact with the support at the appropriate height. In addition, sign mounting height is typically 2.1 m (7 feet) to the bottom of the sign. This height, whether it is 2.1 m (7 feet) or some other tested height, is often critical to the performance of the support when struck by an errant vehicle and subsequently the way the support and its attached components rotate over or interact with the vehicle. The preceding statements also apply to luminaire supports that are currently up to 18.3 m (60 feet) tall.

In summary, when applying a VMS to a support structure, the designer must avoid interfering with the activation and release of the system for it to perform properly. This means keeping the applied VMS from obstructing the displacement of bolts from slip bases, being in the path of the rotating support after it released from its foundation or anchor, or significantly altering the impact height of the errant vehicle by altering the effective ground height around the structure and the vehicle approach to the structure.

Figure 5. Example of a Cast Aluminum Frangible Luminaire (AASHTO 2011b).

Figure 6. Example of a Frangible Coupling Design (AASHTO 2011b).

Roadside Geometric Features and Pavement Discontinuities

As presented in MASH, roadside geometric features and pavement discontinuities are any feature of the roadside that deviates from a flat surface, such as ditches, curbs, embankments, driveways, depressed or elevated medians, drainage structures, and rock cuts. These features should be designed to be traversable by errant vehicles. The AASHTO RDG provides some guidance for the designer for these features. If applying a VMS to these features, the designer should consult the RDG to ensure the geometry of the feature is not adversely changed. For example, by adding a VMS, the slope, any slope rounding present, or the continuity of the surface should not alter from its designed parameters. This means the addition of a VMS should not make a traversable slope non-traversable or create other discontinuities. In addition, as previously discussed, the VMS should not change the approach height or grading leading to and surrounding a highway safety appurtenance such that it would alter the way an impacting vehicle engages with the safety feature.

Summary

VMSs applied in and around highway safety appurtenances should consider their effect on the performance of everything in the highway design environment. If a VMS is thought to possibly influence the performance, then consideration should be given to crash testing the VMS and safety appurtenance together as a system. As of January 1, 2011, all newly developed hardware must be tested following MASH criteria. Of particular interest to the application of VMSs, FHWA also issued a memorandum dated January 7, 2016, regarding the federal-aid eligibility of highway safety hardware. The following applies to VMSs (FHWA 2016):

- FHWA will no longer issue eligibility letters for highway safety hardware that has not been successfully crash tested to the 2016 edition of MASH.
- Modifications of eligible highway safety hardware must use criteria in the 2016 edition of MASH for reevaluation and/or retesting.
- Non-significant modifications of eligible hardware that have a positive or inconsequential effect on safety performance may continue to be evaluated using finite element analysis using simulation models.

LEAVE-OUTS

Strong post (both wood and steel posts) W-beam guardrail is designed to absorb some crash energy through post rotation in the soil. Mow strips or other forms of VMSs can restrict this rotation and adversely affect the impact performance of the guardrail system. A properly designed leave-out area in the VMS around a post permits the required rotation. The leave-out area allows roadside appurtenances such as guardrail to perform properly by permitting the posts to move upon impact without encountering the surrounding, more rigid material surface and enables easier maintenance and repair of the guardrail. These leave-out areas can accumulate litter, debris, sand from winter operations, and windblown soils. Seeds deposited in leave-out areas can take root and create problems. Similar problems can be seen where the VMS abuts the edge of the pavement, as shown in Figure 7. To minimize unwanted vegetation, the leave-out areas are filled with a low-strength cover material to inhibit vegetation growth. Typical leave-out materials include grout, hand-stamped hot-mix asphalt, gravel, emulsified asphalt on gravel, spray foam, Styrofoam, or other similar impervious material.

Figure 7. Weed Growth at the Edge of Pavement (Barton and Budischak 2013).

Some of the first research performed to investigate the design of leave-outs is documented in a Midwest Roadside Safety Facility (MwRSF) report *Development of Guidelines for Placement of Steel Guardrail Posts in Rock* (Rohde 2003). MwRSF studied and documented post deflection characteristics in various embedment configurations using dynamic impact testing and simulation and thereafter developed a steel post W-beam guardrail system for installation in rocky soils. The posts were installed in holes drilled in concrete, constructed by drilling three 203-mm diameter holes on 165-mm centers to a depth of 610 mm. The drilled holes were backfilled with compacted ASTM C33 coarse aggregate, size no. 57. The steel post W-beam guardrail system installed in rock-soil foundations was successfully tested to NCHRP Report 350 Test 3-11.

During the same time, the Texas A&M Transportation Institute (TTI) examined the effect of pavement post encasement on the crashworthiness of strong post guardrail systems to determine the performance of these systems using dynamic impact testing, numerical simulation, and full-scale crash testing (Bligh et al. 2004). Mow strip dimensions, materials, and depths were considered in addition to the presence of leave-out sections around posts. Along with enhanced impact performance and vegetation management, it was suggested that mow strip configurations featuring leave-outs facilitate ease of repair after an impact. Crash tests of a steel post guardrail system and a round wood post guardrail system encased in a concrete mow strip with grout-filled leave-outs were successful performed following NCHRP Report 350 criteria. The Bligh et al. report provides recommendations regarding the acceptable ranges for some key mow strip parameters, like mow strip material and dimensions, leave-out dimensions, leave-out backfill material, and guardrail post location (Bligh et al. 2004).

The research performed by MwRSF and TTI led FHWA to publish memorandum B-64-b, "W-Beam Guardrail Installations in Rock and in Mowing Strips" on March 10, 2004. The memorandum offers guidance developed from the research performed for installing W-beam installations in rock and mow strips. The AASHTO Task Force for Roadside Safety reviewed the research and later included the research findings in the 2011 AASHTO RDG. The RDG information was developed under NCHRP Report 350 guidance. FHWA's "Frequently Asked Questions: Barriers, Terminals, Transitions, Attenuator, and Bridge Railings" currently provides direction to the B-64-b memorandum for guidance (FHWA 2020).

Research conducted by Arrington et al. focused on testing alternative materials for the leave-out sections around guardrail posts encased in a pavement mow strip (Arrington et al. 2009). A two-sack grout mixture that had been successfully crash tested was used as a baseline reference for acceptable impact performance. Static laboratory and dynamic impact testing was conducted to evaluate the various products. The long-term durability of these products was not evaluated.

The products that were investigated include a two-part urethane foam, a molded rubber product that has an insert fabricated to match the size of the leave-out, a flat recycled rubber mat that rests on top of a leave-out backfilled with soil, and a pop-out concrete wedge. All of the products except the flat rubber mat are considered to have acceptable impact performance. The acceleration levels associated with the flat rubber mat significantly exceeded the baseline threshold established from the test results of the two-sack grout mixture. The compacted soil confined within the leave-out was responsible for the higher acceleration. The other tested products were acceptable alternatives for the two-sack grout mix from an impact performance and vegetation control standpoint. However, the advantages and disadvantages regarding cost, availability, ease of installation, and inspection should be considered before selecting a product.

A 2019 study evaluated the MASH performance of a 31-inch-tall W-beam guardrail system with steel and wood posts installed in a concrete mow strip (Sheikh et al. 2019). The 31-inch W-beam guardrail system with steel posts in a concrete mow strip performed acceptably for both MASH Tests 3-10 and 3-11. The steel post W-beam guardrail system in a concrete mow strip is considered to have acceptable performance in accordance with the criteria for MASH TL-3 longitudinal barriers. The 31-inch W-beam guardrail system with 6-inch by 8-inch rectangular wood posts in a concrete mow strip performed acceptably for MASH Test 3-10. However, during MASH Test 3-11, the W-beam rail element ruptured, allowing the 2270P vehicle to penetrate the installation (Sheikh et al. 2019). Similarly, a 31-inch W-beam guardrail system with 7½-inch round wood posts installed in a concrete mow strip with grout-filled leave-outs also failed to meet the MASH TL-3 criteria (Bligh et al. 2020). Both wood post systems were tested with a 40-inch embedment depth.

However, a modified 7½-inch-diameter round wood post system with a reduced embedment of 36 inches was successfully full-scale crash tested in accordance with MASH TL-3 requirements (Moran et al. 2020). A 6-inch by 8-inch rectangular wood post system with 35-inch embedment also met MASH TL-3 criteria (Moran et al. 2021). Therefore, both steel and wood post W-beam guardrail configurations can be used in mow strips with leave-outs, but care should be taken to ensure the proper post configuration and embedment depth. The maximum strength of the grout in the leave-out was increased during this testing from 120 psi to a maximum of 230 psi, which should provide more installation flexibility (Moran et al. 2020).

A steel post W-beam guardrail system installed in simulated rocky terrain following the guidance from the previously cited research (Rohde 2003) and FHWA memorandum B-64-b was successfully tested to MASH TL-3 (Bligh et al. 2019). A round wood post W-beam guardrail system tested in a similar configuration did not satisfy MASH criteria (Bligh et al. 2019).

NON-HERBICIDE, LONG-TERM VMSS

Impervious VMS Treatments

Minor Concrete Pavement

Minor concrete for vegetation control is used in areas requiring a roadside management strategy that eliminates or minimizes the growth of unwanted vegetation. Minor concrete can contain additives such as crumb rubber and polypropylene fibers (see Figure 8). Color can be added to minor concrete. The Caltrans Construction Policy Bulletin, *Minor Concrete Vegetation Control,* indicates the use of this VMS with Midwest guardrail systems and thrie beam barriers (Caltrans 2017b).

Figure 8. Minor Concrete Used for Vegetation Management (Caltrans 2017b).

A further benefit of using minor concrete as a VMS is easy installation using standard equipment during new construction. The RDG (AASHTO 2011b) and MASH (AASHTO 2016) provide leave-out compliance requirements around strong post W-beam guardrail and other systems. Retrofit installation at existing structures may be impractical and not cost-effective due to grading and excavation requirements for this VMS.

Crumb Rubber Modified Concrete

Crumb rubber modified concrete (CRMCrete) is a concrete-based product using a slurry blend of recycled scrap tire crumb rubber material and homopolymer polypropylene high-performance reinforcing fibers. The CRMCrete weed barrier system is installed like minor concrete and can be used with color and texture for increased aesthetic value. Formwork is not always necessary, and this VMS has a higher daily production rate than other surface treatments. Installation is easy and uses standard equipment and concrete mixes. However, because of the consistency of the mix, CRMCrete is not appropriate for steeper slopes.

There is a limited history of maintainability and life cycle costs. As with other colored and/or textured materials, when making repairs, it is difficult to match the original color. The RDG (AASHTO 2011b) and MASH (AASHTO 2016) provide leave-out compliance requirements around strong post W-beam guardrail and other systems (Malcolm 2009).

Caltrans used CRMCrete in a median location with many obstructions for mowing crews such as raised drop inlets, culvert pipes sticking out, survey monuments, signage, posts, and pullboxes. Caltrans made the obstacles flush and reset around the appurtenances using CRMCrete. This made mowing easier and thus reduced employee exposure time in dangerous locations. Caltrans used CRMCrete under the guardrail and around signposts. Caltrans gained approval from FHWA for the use of CRMCrete under the W-beam guardrail system.

Standard Concrete Pavement

Standard concrete is commonly used as a VMS. Concrete can be colored or stamped, making it an option for use in areas with greater aesthetic concerns (shown in Figure 9). The patterns are stamped into the concrete before curing using a patterned form. The color can be surface-applied or integral to the concrete mixture. Leave-outs may be required for some applications due to the rigidity of the material, particularly when used with strong post W-beam guardrail and other systems. The RDG (AASHTO 2011b) and MASH (AASHTO 2016) provide leave-out compliance requirements. Although the relative cost of patterned concrete is greater than many other treatments, it is adaptable to different aesthetic goals, provides a long-term solution, and can be used in slope conditions. Patterned materials with seams are subject to surface accumulation of soil, seeds, and debris (Caltrans 2012).

Figure 9. Standard Concrete Pavement Uses (Sheikh et al. 2019).

Asphalt Concrete Pavement

Asphalt concrete pavement used as a VMS is an applicable strategy in medians and gore areas, under guardrails and cable barriers, and as a mow edge adjacent to structures such as sound walls and retaining walls (Figure 10).

Photo courtesy of Adam Weiser

Figure 10. Asphalt Under Cable Barrier System.

Stamped and colored asphalt concrete can provide many of the same aesthetic advantages of colored, textured concrete and pavers at a reduced cost of installation and maintenance. Installation involves stamping warm, pliable asphalt with a patterned, woven wire template pressed into the asphalt using standard compaction equipment, as shown in Figure 11. The templates are re-used along the course of the area. The color is in the finishing coat and is topically applied. The RDG (AASHTO 2011b) and MASH (AASHTO 2016) provide leave-out compliance requirements when using stamped asphalt concrete around strong post W-beam guardrail and other appurtenances. This VMS should incorporate edge restraints and pavement reinforcement fabric for additional resistance to cracking and deformation (Caltrans 2017c).

Figure 11. Stamped Asphalt Concrete at Roundabout (Pattern Paving Products 2016).

Advantages for using asphalt as a VMS include lower relative initial costs, commonly used installation equipment, and worker knowledge of installation techniques. Limitations include degradation over time due to the lack of compaction with regular traffic use, which may lead to weed growth. Although initial costs are low, minor concrete is more cost-effective in terms of life cycle costs. Stamped asphalts are subject to surface damage, and asphalt base may bleed through surface color in hot climatic conditions. This VMS has limited slope applications, and the durability of stamped asphalt is moderate.

Asphalt Composite

Asphalt composite for vegetation control is a cold, spray-applied asphalt emulsion reinforced with fiberglass strands. This technique provides a solid, seamless impervious surface. Removal of the seams helps eliminate the historically problematic areas where unwanted vegetation typically grows. Figure 12 shows a guardrail system using asphalt composite as a VMS.

Figure 12. Asphalt Composite Treatment at Guardrail System (Caltrans 2017d).

Asphalt composite adheres to asphalt, concrete, wood, and metal. A dilute solution applied at the leading edge adheres to the adjacent loose soil and provides erosion control. One key advantage of using an asphalt composite VMS is the retrofit capabilities under existing guardrails, signs, and other appurtenances. Asphalt composite as a VMS can be simply and quickly installed at existing structures, can be easily repaired, and allows a minimal lane closure period. Asphalt composite can be used in situations where rigid materials such as minor concrete treatment are not practicable. This material is durable enough to withstand machine traffic and flexible enough to move during a guardrail impact. In addition, asphalt composite has a low life cycle cost. One limitation of asphalt composite is that installation requires the temperature to be above 50° F. However, once cured, the VMS can withstand freezing temperatures (Caltrans 2017d).

Modular Paving Units (May Be Pervious Depending on Application)

Modular paving units consist of concrete or brick pavers used as a VMS (see Figure 13). Modular paving units are durable, come in a variety of shapes and colors, and can be a cost-effective treatment. Pavers can sustain both pedestrian and vehicle traffic depending on the specifications of the pavers. This VMS is most used in gores, raised medians, and pedestrian use locations. As with other textured VMSs, soil and debris can accumulate in the paver spaces and provide a medium for unwanted vegetation. Therefore, this VMS may require spot herbicide treatment or other maintenance actions.

Figure 13. Modular Paving Units in Median (TxDOT 2017).

The pavers can be classified as either pervious or impervious depending on the base material used. These modular units can be placed on compacted soils, with or without a geosynthetic fabric (herbicide or non-herbicide treated) using a graded sand fill between pavers or placed on a concrete or other impervious base and filled with a mortar/grout material. One advantage of using a modular unit VMS is the ability to access subsurface utilities and the general ease of repair because pavers can be removed and replaced much more easily than a poured-in-place VMS. Unfortunately, their flexibility is also a disadvantage. The pavers are susceptible to deformation from vehicular traffic, especially heavy trucks. Therefore, the paving foundation needs to be adequate to meet the traffic loads and meet safety requirements for pedestrians and vehicles (TxDOT 2017). If set on an impervious surface using mortar material, leave-outs may be required for some applications due to the rigidity of the material. The RDG (AASHTO 2011b) and MASH (AASHTO 2016) provide leave-out compliance requirements.

Rock Blanket

Rock blanket as a VMS consists of a ground surface covered with rock cobbles at the areas where vegetation control is required. The rock blanket is installed into mortar or concrete and may be used with or without a concrete base. It is a multi-purpose treatment that can be used for aesthetic reasons, erosion control, and weed suppression. Figure 14 shows applications of a rock blanket along the roadside. There are numerous applications for this VMS. Examples include embankment paving, slopes under bridges, medians, and roundabout designs.

Figure 14. Rock Blanket Installations (Diversified Landscape Company 2016, Caltrans 2015).

Rock blankets should not be placed near clear recovery zones or other areas subject to errant vehicles. As with other heavily textured VMSs, rock blankets are subject to the accumulation of deposited soils that can facilitate weed growth. Care should be taken in the design to minimize the spacing between the rocks. Context sensitivity can be achieved through the choice of rock and mortar color. Those areas not using a mortar base should use a geosynthetic fabric (herbicide or non-herbicide treated). An important guideline to follow while placing the rock blanket is to provide a physical barrier between the rock blanket and pedestrians (Caltrans 2015). Leave-outs may be required for some applications due to the rigidity of the material, particularly when used with strong post W-beam guardrail and other systems. The RDG (AASHTO 2011b) and MASH (AASHTO 2016) provide leave-out compliance requirements.

Rubber Weed Mat

The rubber weed mat (Figure 15) is designed to block out sunlight and inhibit plant growth. This VMS is comprised of recycled rubber tires bonded together with a resin and shaped into a mat. Color can be added to reflect the surrounding aesthetic context. As with other textured VMSs, rubber weed mats are subject to the accumulation of deposited soils that can facilitate weed growth. Ground penetration holes can be pre-cut or molded into the product before installation. Rubber weed mats around strong post guardrails and possibly other safety devices whose performance depends on permitting the post or support to rotate in the soil may also require leave-outs to be used in conjunction with their application. As noted in the Arrington et al. (2009) study, one proprietary rubber weed mat failed to permit the desired level of rotation during a dynamic post impact when compared to the resistance offered by a grout-filled leave-out that was successfully crash tested. Installation requires an overlap at seams that are sealed using an asphalt crack sealer or resin adhesive. The tiles are best suited for level areas and are not recommended for large, nonlinear areas (Caltrans 2017e). This VMS is subject to damage from high winds, mowers, snow removal equipment, and ultraviolet (UV) degradation.

Figure 15. Rubber Weed Mat (Caltrans 2017e).

Pervious VMS Treatments

Aggregate Base

Aggregate base is a compactable, graded rock placed on a prepared surface and compacted to 90–95 percent. This VMS can be used in all application areas. Aggregate base is a generally low cost and readily available material. It is suitable for new and some retrofit locations. Figure 16 shows examples from FHWA's *Public Roads* (Meininger and Stokowski 2011) of natural aggregates used in construction. Using aggregate as a VMS may not be applicable in areas with snow removal equipment and snow storage because the VMS can be displaced by errant vehicles and maintenance equipment. This VMS may require spot herbicide treatment and re-compaction.

(a) Natural gravel often used as coarse aggregate in concrete, (b) crushed stone coarse aggregate typically used in asphalt mixtures in paving and concrete, and (c) a compacted crushed stone layer used as granular base material.

Figure 16. Aggregate Base (Meininger and Stokowski 2011).

Asphalt Millings

Asphalt millings used as a VMS are comprised of bituminous material removed during cold planing (the controlled removal of the surface of the existing pavement) operations and are ground or crushed into asphalt milling. The advantage of using this VMS is the easy installation in new construction, repair, and retrofit applications. Limitations include improper compaction of the material, leading to weed problems. Compaction may degrade over time. Environmental concerns are noted if millings erode near watercourses. As with most stockpiled materials, stored millings may accumulate weed seeds.

Glass Cullet

Glass cullet consists of recycled glass processed into a mulch material (see Figure 17). The processing removes the sharp edges and produces a material safe to handle for a variety of uses. Glass cullet's aesthetic value comes from a variety of sizes and colors available from the recycled glass. The material does not decompose and works well in relatively flat areas; it is not recommended for slopes. An edge/border material may be necessary to contain the cullet (Malcolm 2009). As a VMS, cullet is typically applied over a geosynthetic fabric (herbicide or non-herbicide treated), like wood mulch. However, Caltrans installed cullet under guardrail without using a barrier and reports that it is still functional after 7 years. Although there is limited experience in using glass cullet as a VMS, numerous DOTs use glass cullet as aggregate, granular base, and fill and in other applications. The Pennsylvania Department of Transportation (PennDOT) issued a PennDOT Recycled Material Brief, *Crushed Glass Fact Sheet*, in 2013 (PennDOT 2013), explaining PennDOT's use of glass cullet and providing specifications (see Appendix D).

Figure 17. Recycled Glass Cullet Mulch (Malcolm 2006).

Gravel Mulch

Gravel mulch is applied to the soil surface to reduce weed growth and as an aesthetic treatment (Caltrans 2017f). Gravel mulch consists of placing graded, crushed, or quarried rock over a geosynthetic fabric (herbicide or non-herbicide treated). Figure 18 shows the gravel mulch treatment at the roadside. Gravel mulch is one of the least expensive control treatments that can be achieved with the use of existing equipment. One of the biggest limitations of this treatment is that it can be easily dislodged by errant vehicles and should not be used where disruption from errant vehicles is likely. Some of the advantages of using gravel mulch include low maintenance cost, stormwater runoff infiltration, and wind resistance (Davey Tree Expert Company 2017). One of the limitations of gravel mulch is the accumulation of soil and debris that provides a medium for weed growth.

Figure 18. Gravel Mulch Treatment at the Roadside (TxDOT 2017)

Rock Slope Protection

Rock slope protection (also known as rock riprap, dump rock, and others) differs from gravel in size and texture. Rock slope protection consists of larger rocks that are surface applied with or without a geosynthetic fabric (herbicide or non-herbicide treated). This VMS is easy to install with existing equipment. Typical usage is in rural or transition areas, on slopes, under structures, and in other similar locations (see Figure 19). This VMS is not advised for use in areas where errant vehicles may come in contact with it. Rock slopes can be installed on a slope up to 1V:2H. As with other textured VMSs, soil and debris can accumulate and provide a medium for unwanted vegetation. As such, this VMS may require spot herbicide treatment or other maintenance actions.

Figure 19. Rock Slope Protection (Ohio Department of Transportation n.d., Indiana Department of Environmental Management 2007).

Organic Mulch

Organic mulch generally consists of some type of recycled material or by-product, such as chipped wood (see Figure 20). This material can come from ROW clearing operations at a minimal cost to the DOT. Organic mulch may be used as a VMS, but due to its organic structure, degradation/decomposition occurs over time and requires maintenance and/or replacement every 2 to 5 years. This VMS may be subject to displacement by errant vehicles, maintenance equipment, and storm events. This VMS method should be considered as a temporary vegetation control solution for use in areas subject to near-term disruptions (Caltrans 2017g).

Figure 20. Organic Mulch (Pacific Landscape Supply 2019).

Weed Control Fiber Mat

Weed control fiber mats discussed in the Caltrans Roadside Management Toolbox consist of synthetic polyester fibers made from recycled plastics. This VMS works by blocking out sunlight to inhibit plant growth yet allows for the infiltration of stormwater runoff. These mats need to be placed on a semi-level, compacted surface without any underlying debris (see Figure 21). This VMS has many advantages over other treatment methods because it is easy to install at an existing or new roadside location (Caltrans 2017h). Weed control fiber mat is an affordable, easily repairable, and effective measure.

Figure 21. Weed Control Fiber Mat (Caltrans 2017h).

However, weed control fiber mat may have limitations in areas where winter maintenance equipment is used. Research conducted for the Washington State Department of Transportation (WSDOT) examined several weed barriers and found a need for annual removal of accumulated organic/inorganic debris. Without this maintenance, the organic buildup starts to grow grass and weeds. At sites where herbicide use is restricted, weed barriers provide a viable option although it may be prohibitively expensive for normal guardrail locations (Willard et al. 2010).

Select Vegetation Establishment

Irrigated/Ornamental Vegetation

Irrigated/ornamental vegetation as a VMS is used to sustain desirable vegetation that can suppress the growth of weeds, annual grasses, and other undesirable vegetation in specified locations (Caltrans 2017i). This treatment is generally used in urban and suburban locations where there are greater stakeholder expectations for aesthetics, as shown in Figure 22. This control measure is used in lieu of conventional impervious and pervious surface covers. Vegetation is chosen for specific qualities such as maximum height and ability to out-compete weeds. Vegetation has the benefit of providing erosion control, stormwater runoff infiltration, and landscape enhancement. The limitation is that this type of control requires maintenance over its life cycle. Costs vary according to the design parameters.

Figure 22. Irrigated Ornamental Vegetation (TxDOT 2017)

Native and Non-irrigated Vegetation

Like irrigated ornamental vegetation, native and non-irrigated vegetation can be used to suppress unwanted vegetation and replace it with more desirable vegetation (Caltrans 2017j). The advantage of using native plant species is their ability to out-compete weeds and annual grasses when planted on roadsides. The use of this type of vegetation is generally best suited for non-urban areas. Native plant communities generally require less maintenance and can become self-sustaining (see Figure 23). A major advantage of using native vegetation is that many provide habitat for pollinators. Limitations include a slow establishment period that may require maintenance to eliminate unwanted vegetation. Post-construction soils may require an amendment to provide a suitable growing medium.

Figure 23. Native Non-irrigated Vegetation (Arizona DOT 2008)

Comparison of Commonly Used VMSs

Table 2 shows a comparison of the commonly used VMSs. Approximate costs for each VMS were obtained from Caltrans (2017a) pricing and are presented to show relative cost comparisons. The modular paving unit cost reflects the TxDOT 2018 average low bid.

Table 2. Comparison of VMSs (Caltrans 2017a, TxDOT 2019)

VMS	Benefits	Limitations	Installation Cost per Square Yard
Minor concrete pavement	• Effective life cycle cost • Easy installation for new construction • Various colors available	• Not cost-effective for retrofit application • Requires leave-out section	$65*
Standard concrete pavement	• High longevity and low life cycle cost • Use on slopes • Various colors and patterns available	• Repairs difficult • Requires leave-out section	$100–$125*
Asphalt concrete pavement	• Quick and easy installation • Various colors and patterns available	• Requires leave-out section • Subject to surface damage • Limited slope applications	$40–$55*
Asphalt composite	• Low life cycle cost • Easily installed and repaired • Seamless application • Retrofit applications	• Installation requires above 50° F	$52*
Modular paving unit	• Allows for subsurface access such as utilities • Various styles and colors • High aesthetic value • Retrofit applications	• Limited slope application • Subject to damage from heavy vehicles	$75–$90**
Rock blanket	• Wind resistant • Low maintenance costs	• Repairs difficult	$85–$120*
Rock slope protection	• High effective longevity • Easy installation, repairs, and replacement • Slopes up to 2:1	• Low aesthetic appeal	$25–$85*
Rubber weed mat	• New and retrofit construction • Easily repaired/replaced • Colors available • Specialized designs available	• Subject to damage from wind, mowers, winter operations, and UV degradation • Joints may become problematic • Texture may accumulate debris	$53*
Gravel mulch	• Uses common equipment • Low maintenance	• Easily displaced by errant vehicles	$10–$23*

VMS	Benefits	Limitations	Installation Cost per Square Yard
Organic mulch	• Retains soil moisture • Enhances soil structure • Provides erosion control	• Temporary solution • Degrades over time • 2- to 3-year life cycle	$40*
Weed control fiber mat	• Allows for infiltration • UV stable and fire retardant • Easy repairs/replacement • Retrofit applicable but more expensive	• Subject to damage from wind, mowers, and winter maintenance equipment	$50*
Irrigated/ ornamental vegetation	• Slope protection and visual enhancement • Once established, out-competes weeds	• Subject to high initial cost and maintenance • Requires establishment period	$16–$24*
Native and non-irrigated vegetation	• Self-sustaining when established • Out-competes weeds • Potential pollinator habitat	• 3- to 5-year establishment period may require soil amendments and herbicides or other control	$0.90–$9*

* Installation costs reflect Caltrans (2017a) pricing and are presented to show relative cost comparisons.
** Modular paving unit costs reflect the TxDOT average low bid.

Innovative/Alternative VMSs

Numerous VMSs have been used across the country for various treatment areas. These VMS are composed of materials typically found in transportation construction. However, new materials have potential for DOT use.

Geosynthetic Cementitious Composite Mat

Geosynthetic cementitious composite mat (GCCM) is a flexible cement-impregnated fabric that hardens when hydrated to form a thin, durable concrete layer (see Figure 24 and Figure 25). This material has different proprietary names such as Concrete Cloth™ and Concrete Canvas®. Caltrans used Concrete Canvas® in limited locations. DOT use of this VMS was not found to be widespread and had minimal performance measurement data. This VMS consists of:

- Dry concrete mix
- Reinforcing fiber matrix
- Fabric top surface
- Polyvinyl chloride (PVC) bottom coating

Figure 24. Concrete Canvas® GCCM Section (Concrete Canvas 2020).

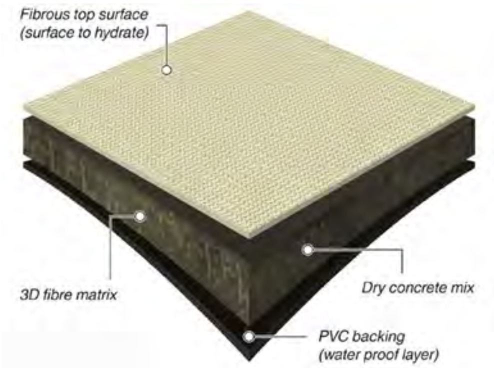

Figure 25. Concrete Cloth™ (Srinivas and Ravinder 2012).

GCCM products have the following benefits:

- Rapid and easy installation
- Product comes on a roll (needing no concrete mixing)
- Waterproof
- Fireproof
- Flexible enough to allow material to conform to a surface
- Unset material can be cut as necessary for a given situation

TRANSPORTATION AGENCY RESEARCH

Transportation agencies are trying to find cost-effective, low-maintenance solutions for maintaining a vegetation-free zone in critical areas. However, these VMSs must work in conjunction with the safety parameters for guardrail and other fixed objects on the roadside.

Delaware Department of Transportation

The Delaware Department of Transportation (DelDOT) funded a study to explore various methods of treating vegetation under guardrail (Barton and Budischak 2013). This study examined three herbicide formulations, four weed control barriers, and competitive vegetation. The four VMSs investigated included:

- Permeable recycled fiber mat
- Permeable recycled fiber mat customized to fit the edge of the roadway and variances in guardrail post width
- Semi-rigid, interlocking panels made of 100 percent recycled plastic (this product is no longer available)
- Rubber matting with three punched guardrail cutouts to provide flexibility for installation

Figure 26 shows the four VMSs used in this study.

Permeable recycled fiber mat, standard installation

Permeable recycled fiber mat, custom installation

Semi-rigid, interlocking plastic panels

Rubber matting with punched guardrail cutouts

Figure 26. Weed Control Barriers Evaluated in DelDOT Study (Barton and Budischak, 2013).

Barton and Budischak (2013) found that weed control barriers are difficult to install in retrofit applications. As with other VMSs, random weed growth is somewhat problematic. The caulk areas were the weakest point in the systems and allowed for breakthrough vegetation growth. Another key point of the research was that new products and systems are subject to installation errors.

Table 3 shows a cost comparison for the weed barriers tested. According to Barton and Budischak (2013), “When you consider amortization over a 10-year life span, weed control barriers are still the most expensive vegetation control option under guardrail. They may be warranted in highly sensitive areas where herbicide use is unacceptable or other conditions warrant the complete lack of vegetation under guardrail.”

Table 3. DelDOT Weed Barrier and Competitive Vegetation Cost Comparison (Barton and Budischak 2013).

Treatment	Installation Cost (per 100 Linear Feet of Guardrail)	Yearly Maintenance Cost (per 100 Linear Feet of Guardrail)	Installation Cost Amortized over 10 Years (per 100 Linear Feet of Guardrail)	Total Yearly Cost Including Amortized Installation Cost (per 100 Linear Feet of Guardrail)
Permeable recycled fiber mat, standard installation	$1789.52	$24.00[1]	$178.95	$202.95
Permeable recycled fiber mat, custom installation	$2197.54	$8.00[2]	$219.75	$227.75
Semi-rigid, interlocking plastic panels	$2607.00	$0.00	$260.70	$260.70
Rubber matting with punched guardrail cutouts	$2537.17	$24.00[1]	$253.72	$277.72
Low fescue	$444.33	$47.02[3]	$44.43	$75.34
Hand trimming	$0.00	$24.00[1]	$0.00	$24.00
Zoysia sod	$1,582.28	$0.00	$158.23	$158.23
Zoysia seed	$45.28	$16.00[4]	$34.53	$50.53
FlightTurf	$541.93	TBD	$54.19	$54.19

[1] Includes 1.5 hand trims/100 linear feet, no herbicide treatment

[2] Includes 0.5 hand trims/100 linear feet, no herbicide treatment

[3] Includes 1.5 hand trims/100 linear feet and 1.25 herbicide treatments/100 linear feet (the herbicide treatment for low fescue is assumed to be required for 3 years until the low fescue stand becomes thick enough to out-compete other vegetation)

[4] Includes one hand trim/100 linear feet (this is based on only one year of data and assumed to be at least 1.5 times in future years)

In addition to cost, the DelDOT study included an evaluation of effectiveness in controlling weeds and suitability for use with guardrails. Table 4 presents these results using ratings on a Likert scale of 1 to 5. For suitability, a 5 indicates the guardrail was uncompromised; for weed control, a 5 indicates no weeds present.

Table 4. DelDOT VMS Suitability and Weed Control Rating (Barton and Budischak 2013).

Treatment	DelDOT Suitability		Weed Control	
	2011	2012	2011	2012
Permeable recycled fiber mat, standard installation	3.72	3.25	2.95	2.80
Permeable recycled fiber mat, custom installation	5.00	0.87	4.83	4.58
Rubber matting with punched guardrail cutouts	4.58	4.20	4.43	3.83
Low fescue	3.37	4.20	0.93	3.44
Zoysia sod	—	4.93	—	4.47
Zoysia seed	—	4.00	—	2.27
Hand trim	3.82	3.77	3.09	2.87

Georgia Department of Transportation

The Georgia Department of Transportation (GDOT) authorized tests to be performed on guardrail installed in accordance with GDOT Standard Detail S-4-2002, which was used in Georgia prior to 2017 and included an asphalt mow strip with a nearby curb. In March 2017, GDOT directed that all new guardrail construction projects on Georgia roadways use asphalt layers that are paved up to the face of the post, leaving the post itself and the area behind unrestrained (Scott et al. 2018).

Iowa Department of Transportation

In 2002 the Iowa DOT examined vegetation control mats made from tire crumb rubber bound together with a urethane resin for use around roadside delineator and guardrail posts. The study also weighed the cost of purchasing and placing the mats versus hand trimming costs. Iowa DOT was looking for a product that would reduce the need for hand trimming and, therefore, maintenance worker exposure in high-traffic areas. Results determined that the mats performed adequately and could have a significant impact on maintenance worker safety (Dunn 2002).

Texas Department of Transportation

TxDOT also conducted a demonstration study using the same tire crumb rubber mats. As with the Iowa DOT study, the areas of concern were around signposts and guardrail posts. This research effort found the following advantages of this VMS:

- Minimizes labor and material costs
- Achieves aesthetic goals
- Uses recycled material (scrap tire crumb rubber)
- Reduces environmental damage from emissions from string-trimming and herbicide use (TxDOT 2012).

Figure 27 shows the recycled crumb rubber VMSs used for the project. The installation process for the demonstration project is in Appendix A.

Figure 27. TxDOT Demonstration Project Using Crumb Rubber VMS (TxDOT 2012).

TxDOT's *Cable Median Barrier Maintenance Manual* (TxDOT 2008) suggests several different mow strip designs (concrete, asphalt, and rip rap) with typical installation cost per mile ranging from $45,000 to $55,000 for concrete and $75,000 to $90,000 for asphalt. TxDOT encourages the use of mow strips to reduce hand mowing or herbicide operations due to the cable barrier system installation. Additionally, a mow strip provides additional resistance to the movement of socket foundations (see Figure 28). Designers should consider mower widths when determining the appropriate distance between the edge of a travel lane and the cable barrier (TxDOT 2008).

Figure 28. Cable Barrier and Roadside Vegetation (TxDOT 2008).

Washington State Department of Transportation

WSDOT conducted a study in 2005 to investigate various vegetative control methods (Willard et al. 2010). Among these were weed barrier mats placed under guardrail. The study showed a maintenance requirement for all products that include the removal of organic and inorganic debris accumulation at the product edge and at seams. The use of pavement or other types of impervious VMSs is best under guardrail, especially in environmentally sensitive areas that prohibit the use of herbicide control treatments.

The research looked at eastern and western Washington climates to determine the effects of climate on the product installation and performance. Table 5 shows the products tested and results.

Table 5. WSDOT VMS Results (Willard et al. 2010).

VMS	Location	Product Description	Maintenance Costs	Findings/Recommendations
Western Washington				
Site 1 Permeable recycled fiber mat, standard installation	Under guardrail	Woven fiber permeable mat	$22/mile/year	This is the oldest WSDOT installation of this product (2002), and this location requires annual removal of accumulated debris.
Site 2 Permeable recycled fiber mat, standard installation	Under guardrail, behind an asphalt curb, with limited overhanging tree canopy	Woven fiber permeable mat	$22/mile/year	This installation performed much better than the other installations of the same product.
Site 3 Permeable recycled fiber mat, standard installation	Under guardrail, extensive existing weeds and brush	Woven fiber permeable mat	$195/mile/year	Weed growth through the material at the edges and joints.
Recycled tire material and adhesive blown by hose	Under guardrail	Ground-up tire mulch, placed over weed fabric, sealed with polyurethane coating	$37/mile/year	Within 2 years after installation, weeds and grass began to seed in over the top. This product is no longer marketed for roadside use.
Semi-rigid, interlocking plastic panels	Under guardrail	Interlocking molded plastic tiles	$22/mile/year	The product as installed was brittle and subject to cracking. This was a prototype product, and the manufacturer has since improved the design and durability.
Rubber matting with punched guardrail cutouts	Under guardrail	Interlocking rubber tiles made of recycled materials	$22/mile/year	The most expensive material of the weed barriers but easiest to install. It is durable and functional in preventing vegetative growth.

VMS	Location	Product Description	Maintenance Costs	Findings/Recommendations
Pavement	Under guardrail	Pavement under guardrail	$895/mile/year	Of all the under-guardrail barriers, this is the least expensive to install and most durable. Maintenance costs would be comparable to those above ($22/mile) if cleaned annually. *
Eastern Washington				
Rubber matting with punched guardrail cutouts	Under guardrail	Interlocking rubber tiles made of recycled materials	$22/mile/year	Relatively easy to retrofit to an existing guardrail, this product performed very well with little maintenance costs. Extremely expensive installation cost precludes this from most sites.
Semi-rigid, interlocking plastic panels	Under guardrail	Interlocking molded plastic tiles	$22/mile/year	This product was relatively difficult to install and suffered significant damage throughout the test. This was a prototype product, and the manufacturer has since improved the design and durability.
Permeable recycled fiber mat, standard installation	Under guardrail	Woven fiber permeable mat	$22/mile/year	Installed in an area with significant snowfall and snow and ice operations. The product performed very well with minimal maintenance costs. Extremely expensive installation cost precludes this from most sites.

* **Initial installation cost:** $18,480/mile. Installation costs estimated based on current average bid prices for asphaltic pavement on WSDOT projects, assuming guardrail can be installed through the pavement at the same cost as it would off the edge of pavement.
Ongoing maintenance cost: $895/mile/year. Cleaning paved shoulder under guardrail once every 7 years: $6,265/mile.

SUMMARY

One difficulty the research team encountered over the course of this project was in identifying specific VMSs used by DOTs. Many of the VMSs placed under guardrail and cable barriers and in other locations are not identified in the DOT literature, manuals, and/or specifications as VMSs. They are simply part of a larger construction component. While there is a growing body of research and project implementation regarding the use of standard-type VMSs (i.e., concrete and asphalt) and emerging products within the industry, few studies have been conducted on product longevity and performance. For many DOTs, implementation and/or demonstration projects using new techniques and/or products are the most assured method of gathering the necessary data to determine whether a VMS will become a DOT standard. Therefore, data regarding their use, cost, effectiveness, and other related issues are limited unless specifically tracked by the DOT or as part of a research project.

The relationship between rigid VMS materials and roadside appurtenances is a critical component of roadside safety. Each rigid material VMS presented reacts with the roadside appurtenance in a specific manner. In application areas such as guardrail, leave-outs may be required to maintain compliance with the RDG and MASH as well as requirements specific to the respective DOT. Many barrier systems are undergoing retesting for compliance. Further, proprietary systems have specific requirements. Therefore, it is imperative for the user to check with current requirements for the specific appurtenance and VMS selected for use.

Cost is a concern for DOTs. Material choice needs to consider a broad range of issues. As found in the Iowa DOT study (Dunn 2002), DOTs need to weigh the cost of materials and installation versus maintenance worker exposure in high-traffic areas. Some VMSs may have a low initial cost but are labor intensive to install and maintain. Another consideration is the environmental impact of various VMSs. In environmentally sensitive areas where herbicide use is unacceptable, highly effective VMSs are a key decision factor over material and installation costs.

Finally, worker safety is a key issue for state DOTs and was a major impetus for this research. The use of VMSs can reduce the need for routine vegetation management activities on the roadside, thus reducing worker exposure to traffic. Worker exposure is also an important consideration when evaluating installation requirements for a specific VMS.

Selecting a VMS requires consideration of many advantages and disadvantages including potential interactions with roadside safety appurtenances, weed control performance, worker exposure, maintenance requirements, installation requirements, cost, and availability.

CHAPTER 3. STATE TRANSPORTATION AGENCY PRACTICES

One of the objectives of NCHRP 14-41, Long-Term Vegetation Management Strategies for Roadsides and Roadside Appurtenances, is to collect information on current practices used by DOTs, institutional obstacles, and the concerns that state agencies have regarding VMS treatments. This chapter summarizes DOTs' use of non-herbicide, long-term VMSs that are designed to prevent or significantly retard the growth of unwanted vegetation around roadside appurtenances and along roadsides. This chapter includes the survey of practice sent to all DOTs, follow-up interviews with select DOTs, and information regarding state DOT documents for VMS treatments. Researchers identified additional methods and technologies that DOTs are piloting, additional guidance required, and how DOTs would use the findings from this research.

SURVEY OF PRACTICE

The NCHRP 14-41 web-based survey and interview process were designed to optimize responses by balancing the length and level of detail requested of the respondents. The draft survey and interview questionnaire were reviewed by the Institutional Review Board for Human Subject Protocols for compliance and sent to the NCHRP panel for approval prior to deployment.

The original project title was Permanent Vegetation Control Treatments for Roadsides, using the acronym PVC. Over the course of the project, the title was revised to Long-Term Vegetation Management Strategies for Roadsides and Roadside Appurtenances, using the acronym VMS. There was confusion over the use of the acronym PVC, and it was determined that long-term was a more accurate descriptor than permanent for the materials presented. The original survey retains the original title and acronym use. However, the survey results show VMS as the acronym.

An email invitation to participate in the web-based survey was sent to the maintenance directors at all state DOTs. The research team sent two reminder emails to non-responding agencies requesting completion of the survey by the requested date. The objectives of the survey were the following:

- Gather information on current practices, institutional obstacles, and the concerns that DOTs have regarding VMS treatments
- Gather information on the selection process implemented by DOTs
- Identify any missing applications that require further guidance (e.g., controls for use with cable barriers)
- Identify any innovative methods or technologies that DOTs have experimented with
- Gather information on any additional guidance that is required

Seventeen states responded to the survey, with some states giving multiple responses based on regional differences. Respondents included vegetation managers, maintenance engineers, roadside environment managers, and other staff responsible for designing and maintaining roadsides. This chapter highlights the key findings of the survey. Figure 29 illustrates the U.S. map showing the DOTs that responded to the survey. Table 6 lists the respondents.

Figure 29. Survey Responses by State.

Table 6. State DOT Survey Respondents.

State	Title	Agency/Organization
AR	State maintenance engineer	Arkansas Department of Transportation
AZ	Roadside resource specialist	Arizona Department of Transportation
CA	Senior landscape architect	California Department of Transportation
CT	N/A	Connecticut Department of Transportation
ID	Roadside program manager	Idaho Transportation Department
IN	Roadside maintenance specialist	Indiana Department of Transportation
KS	Bureau chief of maintenance	Kansas Department of Transportation
KY	Roadside environment state administrator	Kentucky Transportation Cabinet
ND	State maintenance engineer	North Dakota Department of Transportation
NV	Chief maintenance and asset management engineer	Nevada Department of Transportation
RI	State highway maintenance operations engineer	Rhode Island Department of Transportation
SC	Vegetation manager	South Carolina Department of Transportation
TN	Transportation manager 2	Tennessee Department of Transportation
TX	Director of maintenance	TxDOT
VT	Stormwater tech	Vermont Agency of Transportation
VA	State roadside vegetation manager	Virginia Department of Transportation
WV	Assistant director of Maintenance Division	West Virginia Department of Transportation/ Division of Highways

The survey contained multiple questions related to vegetation control treatments, such as current state practices, institutional obstacles, and the concerns that agencies have regarding VMS treatments. Table 7 lists the questions used for this survey.

Table 7. Survey Questions.

Question Number	Survey Question
1	Survey introduction and instructions.
2	Contact information (name, agency, location, area of responsibility, state, title, address, and phone number).
3	Does your agency currently use non-herbicide PVC for preventing or significantly retarding the growth of unwanted vegetation around roadside appurtenances and along roadsides?
4	Does your agency have a published/established protocol for using non-herbicide PVC?
5	If yes, please provide the most current document and/or a website link in the text box below. If the document is not publicly available through your agency's website (i.e., internal to the agency), please submit the document via email at PVC@tti.tamu.edu.
6	If your agency does not have an established protocol, please provide any details of non-herbicide PVC methods or practices currently underway within your agency or region in the space below or in a return email at PVC@tti.tamu.edu.
7	Has your agency collected data or performed research regarding any of the following worker safety aspects of the performance of non-herbicide PVC? Please select all that apply. (Choices: installation, maintenance).
8	Has your agency collected data or performed research regarding any of the following cost aspects of the performance of non-herbicide PVC? Please select all that apply. (Choices: installation, maintenance, direct labor, materials, equipment, management/planning).
9	Has your agency collected data or performed research regarding any of the following material performance aspects of the performance of non-herbicide PVC? Please select all that apply. (Choices: material integrity, longevity, ease of installation, retrofit capabilities, maintenance, impacts of mowing, impacts of ice/snow, impacts of storm water runoff, effectiveness).
10	Has your agency collected data or performed research regarding any additional aspects of the performance of non-herbicide PVC? If yes, please describe.
11	If you selected any of the performance aspect options above, please provide the most current document and/or a website link.
12	If you have PVC performance data that is NOT compiled in a formal document, please supply.
13	In what locations does your agency use non-herbicide PVC? Please select all that apply. (Choices: guardrails, median barrier systems, edge of pavement, gore areas, embankments, other [please specify]) Question 13: In what locations does your agency use non-herbicide PVC? Please select all that apply. Other (please specify). Narration.
14	If you selected any of the options above, please provide the most current document and/or a website link. If the document is not publicly available through your agency's website (i.e., internal to the agency), please submit the document via email at PVC@tti.tamu.edu.
15	If your agency does not have an established protocol, please provide details of PVC implementation in the space provided or in a return email at PVC@tti.tamu.edu.

Question Number	Survey Question
16	What types of non-herbicide PVC does your agency currently use? (Choices: minor concrete pavement, standard concrete pavement, asphalt concrete pavement, rock blanket, gravel mulch, weed control mat [fiber], irrigated/ornamental vegetation, native and non-irrigated vegetation, rubber weed mat, organic mulch, asphalt composite, other [please specify]) Question 16: What types of non-herbicide PVC does your agency currently use? Other (please specify). Narration.
17	If applicable, please provide information regarding other types of PVC usage.
18	If your agency no longer uses a specific non-herbicide PVC, please provide details regarding performance and/or reason for discontinuing use in the space below or in a return email at PVC@tti.tamu.edu.
19	What selection criteria does your agency use regarding the type of non-herbicide PVC specified? Select all that apply. (Choices: roadway context, e.g., urban, suburban, rural; aesthetics; other [please specify]) Question 19: What selection criteria does your agency use regarding the type of non-herbicide PVC specified? Select all that apply. Other (please specify). Narration.
20	Please provide details below regarding information your agency considers important for inclusion in a guidance tool for selecting appropriate non-herbicide PVC or in an email at PVC@tti.tamu.edu.
21	May we contact you for a follow-up mail and/or telephone interview?

PRACTITIONER SURVEY RESULTS

The survey responses are listed in the following tables. The focus is on DOTs' use of non-herbicide VMSs for preventing or significantly retarding the growth of unwanted vegetation around roadside appurtenances and along roadsides. Table 8 shows results for Questions 3 and 4.

Table 8. Responses for Survey Questions 3 and 4.

Question Number	"Yes" Response	"No" Response or Skipped Question
3	AR, AZ, CA, ID, NV, ND, RI, TX	CT, IN, KS, KY, SC, TN, VT, VA, WV
4	AR, AZ, CA, TX	CT, ID, IN, KS, KY, NV, ND, RI, SC, TN, VT, VA, WV

Note: CT and KY answered "no" to Questions 3 and 4; however, they submitted replies to the subsequent survey questions.

Arkansas, California, North Dakota, Nevada, and Texas supplied documents/website links to their VMS documents in response to Question 5, as shown in Table 9.

Table 9. Responses for Survey Question 5.

State	"Yes" Response
AR	Arkansas State Highway and Transportation Department (ARDOT) *Standard Specifications of Highway Construction* 2014 edition https://www.arkansashighways.com/standard_spec/2014/2014SpecBook.pdf
CA	Caltrans Roadside Management Toolbox www.dot.ca.gov/design/lap/landscape-design/roadside-toolbox/index.html www.dot.ca.gov/design/lap/landscape-design/research/weed-and-pest-research.html
ND	The only area we are doing this is using asphalt under guardrail.
NV	We do not have protocols for using non-herbicide VMSs, but it is the policy of the State of Nevada that landscape and aesthetics will be considered along with all other design factors in all transportation projects throughout their life cycles. Please see the link for more information. https://www.nevadadot.com/projects-programs/landscape-aesthetics
TX	Metal Beam Guard Fence (Mow Strip) MBGF(MS)-19 https://www.dot.state.tx.us/insdtdot/orgchart/cmd/cserve/standard/rdwylse.htm#BARRIER(STEEL)

Question 6 requested information regarding non-herbicide VMS methods or practices currently underway that may not be included in a published document. Table 10 shows these responses. Most of the agencies without a published protocol reported the use of concrete, mulch, or some other kind of aggregate material.

Table 10. Responses for Survey Question 6.

State	Response
AR	Aggregate material, asphalt, or concrete along wire rope safety fence mow strip, guardrail, median barrier, edge of pavement, ditch paving, and other non-vegetated areas. Filter blanket and rip rap slopes.
CA	We also use copious amounts of gravel mulch, wood mulch, and paving (pervious if possible) to minimize areas where unwanted vegetation can grow. There is not a statewide protocol to decide which non-herbicide VMS methods are used, but there are standard guidelines in place for this. Standards available at the link. http://ppmoe.dot.ca.gov/des/oe/construction-contract-standards.html
ID	We use mowing, disking, grading, rock armor, concrete surface treatments, mats, and non-irrigated native vegetation.
IN	We do place aggregate/millings or concrete in some cases under some infrastructure.
ND	The only area we are doing this is using asphalt under guardrail.
NV	In urban areas, we use rock mulch and decomposed granite.
RI	We have begun using asphalt millings under and around guardrail and other areas where vegetation growth is problematic.
TX	We treat guardrails in high-traffic areas with concrete.

Table 11 shows the worker safety research data categories collected for Question 7. California and Connecticut have conducted research in the areas of installation and maintenance, while Texas has only conducted research concerning installation.

Table 11. Responses for Survey Question 7.

State	Worker Safety Aspect	
	Installation	Maintenance
AR, ID, IN, KS, KY, ND, NV, RI, SC, TN, VA, VT, WV	Not Applicable	Not Applicable
CA	Yes	Yes
CT	Yes	Yes
TX	Yes	No

Table 12 shows the responses to the request for data regarding cost aspects of the performance of non-herbicide VMSs. The most common research conducted by DOTs is regarding material costs, with California, Connecticut, and Texas all having conducted research.

Table 12. Responses for Survey Question 8.

State	Cost Aspect					
	Installation	Maintenance	Equipment	Materials	Direct Labor	Management/ Planning
AR, ID, IN, KS, KY, ND, NV, RI, SC, TN, VA, VT, WV	N/A	N/A	N/A	N/A	N/A	N/A
CA	Yes	Yes	Yes	Yes	Yes	Yes
CT	Yes	Yes	No	Yes	No	No
TX	No	Yes	Yes	Yes	Yes	No

N/A = Not Applicable

Table 13 shows the material performance aspects reported by different agencies.

Table 13. Responses for Survey Question 9.

State	Material Performance Aspect*									
	MI	L	EI	R	M	IM	ICS	ISW	E	MIL
ID, IN, KS, KY, ND, NV, SC, TN, VA, VT, WV	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
CA	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
CT	No	Yes	No	No	No	No	No	No	No	Yes
RI	Yes	Yes	Yes	No	Yes	No	No	No	Yes	Yes
TX	Yes	Yes	Yes	Yes	Yes	No	No	Yes	No	Yes

* MI = material integrity, L = longevity, EI = ease of installation, R = retrofit capabilities, M = maintenance, IM = impacts of mowing, ICS = impacts of ice/snow, ISW = impacts of storm water runoff, E = effectiveness, MIL = material integrity longevity
N/A = Not Applicable

Table 14 shows the additional research relevant to VMSs that different agencies collected.

Table 14. Responses for Survey Questions 10 and 11.

State	Response
CA	Anecdotal information sharing between districts on performance. Multiple research topics. Please see the research at these locations. http://www.dot.ca.gov/design/lap/landscape-design/research/weed-and-pest-research.html http://www.dot.ca.gov/design/lap/landscape-design/roadside-toolbox/index.html
NV	We only collect labor, materials, and equipment usage for landscape maintenance in general.
TX	We tried ground rubber tires, but after installation and a few rainstorms, they all washed away.

Question 12 requests the respondent provide VMS performance data that are not compiled in a formal document. Table 15 shows the responses.

Table 15. Responses for Survey Question 12.

State	Response
CA	Rubber mats have limited longevity under guardrail. Minor concrete is more effective but takes considerably longer to repair after a guardrail hit. Most often, field maintenance does not repair the concrete.
CT	The Connecticut Department of Transportation has used both processed aggregate and bituminous on projects in the past, only below new guiderail. Based on the limited success and maintenance issues associated with those projects, the specification was revised to turf establishment, which currently is controlled with herbicides.
RI	It [asphalt millings] works well initially, but it does not last as long as we would like. It is not a permanent solution.

Table 16 lists the locations where non-herbicide VMSs are used. All respondents using VMSs listed guardrails. Most of the respondents also use VMSs at median barrier systems and along the edge of the pavement. The other locations include signposts, gore areas, embankments, and medians.

Table 16. Responses for Survey Question 13.

State	Location							
	Guardrails	Cable Barrier	Sign Posts	Edge of Pavement	Gore Areas	Embankments	Medians	Other
IN, KS, SC, TN, VA, VT, WV	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
AR	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No
CA	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
CT	Yes	No	No	No	No	No	No	No
ID	Yes	No	No	Yes	Yes	No	Yes	No
KY	Yes	Yes	No	No	No	No	No	No
ND	Yes	No	No	No	No	No	No	No
NV	Yes	Yes	No	Yes	No	No	Yes	No
RI	Yes	Yes	No	Yes	No	No	No	No
TX	Yes	Yes	No	Yes	Yes	Yes	No	Yes

California listed the other location as slope paving under structures. Texas stated VMSs are used at rest areas and travel centers.

Table 17. Responses for Survey Question 14.

State	Response (Documents and/or Website)
AR	ARDOT *Standard Specifications for Highway Construction* 2014 edition http://web/standard_specifications.aspx
CA	http://www.dot.ca.gov/design/lap/landscape-design/roadside-toolbox/index.html
ID	https://apps.itd.idaho.gov/apps/manuals/OperationsManual/Operations_Manual.pdf https://itd.idaho.gov/env/?target=BMP-Manual/

Table 18 lists individual responses for Question 15, providing respondents' details of VMS implementation if they do not have an established protocol.

Table 18. Responses for Survey Question 15.

State	Response (Details)
ID	We only have a protocol for mowing and non-irrigated vegetation. https://apps.itd.idaho.gov/apps/manuals/OperationsManual/Operations_Manual.pdf
KY	Chip seal is commonly used as a VMS on most new road construction and rehabilitation of existing highways. Concrete apron is used as a VMS on all median cable barrier.

Table 19 has the responses for the types of non-herbicide VMSs used. The most common VMS types reported by the respondents are minor concrete pavement, asphalt, gravel, and native and non-irrigation vegetation.

Table 19. Responses for Survey Question 16.

State	Types of Non-herbicide VMS*											
	MCP	SCP	ACP	AC	RB	RWM	GM	OM	WCM	IOV	NIV	Other
KS, SC, TN, VA, VT, WV	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
AR	Yes	No	Yes	No	No	No	Yes	No	No	No	Yes	Yes
CA	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No
CT	No	No	Yes	No	No	No	Yes	No	No	No	No	No
ID	Yes	No	No	No	Yes	No	Yes	No	Yes	Yes	Yes	No
IN	Yes	No	Yes	No	No	No	No	No	No	No	Yes	Yes
KY	Yes	No	No	Yes	No	No	No	No	No	No	No	No
ND	No	No	Yes	No	No	No	No	No	No	No	No	No
NV	No	No	No	No	Yes	No	Yes	No	Yes	Yes	Yes	No
RI	No	No	No	No	No	No	No	Yes	No	No	No	Yes
TX	Yes	Yes	Yes	Yes	No	Yes	No	Yes	Yes	No	No	Yes
Total	6	2	6	3	3	2	5	3	4	3	5	4

* MCP = minor concrete pavement, SCP = standard concrete pavement, ACP = asphalt concrete pavement, AC = asphalt composite, RB = rock blanket, RWM = rubber weed mat, GM = gravel mulch, OM = organic mulch, WCM = weed control mat (fiber), IOV = irrigated/ornamental vegetation, NIV = native and non-irrigated vegetation

Individual responses for Question 15 include asphalt millings used by Indiana and Rhode Island. Arkansas and Texas use rock rip rap, a rocky rubble material that is placed on roadsides.

Question 17 requested information regarding alternative types of VMS usage. Table 20 shows the responses. A malfunction with the survey question did not allow for multiple selections.

Table 20. Responses for Survey Question 17.

State	Response (Other Types of VMS Usage)
CA	Crumbcrete—version of concrete using crumb rubber as the aggregate.
ID	https://apps.itd.idaho.gov/apps/manuals/OperationsManual/Operations_Manual.pdf https://itd.idaho.gov/env/?target=BMP-Manual/
TX	Rock riprap is placed under bridges and low light areas.

Question 18 requested information regarding the reasons for discontinuation of using a specific non-herbicide VMS. California reported the inadequate longevity of weed control fiber mats and rubber mats; it also cited the cost and additional requirements of using concrete.

Table 21 shows the responses regarding the selection criteria used to choose which type of non-herbicide VMS should be used.

Table 21. Responses for Survey Question 19.

State	Roadway Context	Roadway Classification	Aesthetics	Performance of Roadside Appurtenances	Other
CT, IN, KS, SC, TN, VA, VT, WV	N/A	N/A	N/A	N/A	N/A
AR	Yes	No	No	No	No
CA	Yes	Yes	Yes	Yes	Yes
ID	No	No	No	No	Yes
KY	No	Yes	No	No	No
ND	No	No	No	No	Yes
NV	No	No	Yes	No	No
RI	No	No	No	Yes	No
TX	Yes	Yes	No	No	No

Table 22 shows the responses of agencies that selected “other” for Question 19.

Table 22. Responses for Survey Question 19.

State	Response (Other)
CA	Roadway context, classification, geometry, aesthetics
ID	All of the above
ND	Standard practice

Table 23 provides details that the agencies consider important for inclusion in a guidance tool for selecting appropriate non-herbicide VMSs. Indiana reported ease and cost of installation and maintenance to be important details used as guidance. California listed the cost-benefit ratio, longevity, and ease of replacement. Idaho reported the type and longevity of both short- and long-term VMSs, the environments where it would be most effective, cost, and installation and maintenance needs.

Table 23. Responses for Survey Question 20.

State	Response
CA	• Mainline structural section for treatments in gore areas • Maintenance preference for selection of VMS treatments • Corridor themes for the type of treatment and color preferences • Cost-benefit ratio • Longevity • Ease of replacement • Context sensitivity, considering any existing corridor master plans, ease of maintenance (we do not use rock blanket where maintenance can use sweepers because they say that it requires hand sweeping/blowing), stormwater considerations, fire safety (wood mulch vs. gravel mulch), and overall cost
CT	We would focus efforts on environmentally sensitive areas.
ID	Consideration should include short-term VMSs (including type and longevity) and long- term VMSs (including type and longevity), area(s) or environment where it is most effective and practical, selection criteria (listed above), cost, installation, and maintenance needs of the item, etc.
IN	• Cost of installation • Cost to maintain • Ease of installation • Ease of maintenance.
TX	Been using concrete on all guardrail and cable barriers across the state.

Summary of Survey Results

The results of the survey of practice revealed few new and innovative practices by the DOTs. Most of the VMSs listed are those found in the 2011 AASHTO *Guidelines for Vegetation Management* (AASHTO 2011a). Researchers found difficulty in gathering information because VMSs are often not specified as such. They are part of a greater design/construction element. While the material used serves as a VMS, it is not designated as such in the design/construction specifications and details. For example, placing concrete under guardrail is part of many guardrail construction manuals and/or specifications. One of the main reasons for using concrete under guardrail is to prevent vegetative growth at that location. However, concrete at similar locations is generally not labeled as a VMS. Searches within DOT websites and other online sources for VMSs led to herbicide-related vegetation management practices.

OTHER STATE DOT PRACTICES THAT PERFORM AS VMSS

The research also collected information about other DOT practices that are not defined as a VMS in state DOT design specifications but behave as a VMS. Examples include:

- Alabama DOT's *Standard Specifications for Highway Construction*, 2006 edition (Alabama Department of Transportation 2006)
  - Aggregate slope protection
  - Riprap
  - Slope paving slope
  - Concrete median strip
- ARDOT *Standard Specification for Highway Construction*, 2014 edition (ARDOT 2014)

  - Concrete island (Section 632)
- Arizona Department of Transportation (ADOT) *Standard Specifications for Road and Bridge Construction* (ADOT 2008)
  - Concrete gore paving (Item 919-1)
- Colorado Department of Transportation (CDOT) *Standard Specifications for Road and Bridge Construction* (CDOT 2017)
  - Median cover material using bituminous median cover material, concrete, patterned concrete, and/or stone
- Minnesota Department of Transportation (MnDOT) *Standard Specifications for Construction*, 2018 edition (MnDOT 2018)
  - Slope paving choices of concrete and stabilized aggregate
- Wyoming Department of Transportation (WYDOT) *Standard Specifications for Road and Bridge Construction* (WYDOT 2010)
  - Minor concrete paving

CHAPTER 4. CASE EXAMPLES

Interviews conducted by the research team were aimed at gathering more detailed information regarding DOT usage of VMSs. States were selected based on the survey results. The objectives of the in-depth phone interviews were to obtain detailed information on innovative selection processes implemented, experiences with implementing innovative methods or technologies, additional guidance required, and how DOTs would use the findings from this research. The states selected for follow-up interviews were California, Idaho, Rhode Island, and Texas. Researchers requested that the selected DOT interviewees provide available information on the use of VMSs, such as specifications, manuals, or any written information.

Follow-up interview questions are as follows:

1. Are you familiar with the AASHTO *Guidelines for Vegetation Management*?
2. Do your specifications/manuals specifically identify VMSs? Or are VMSs part of a greater design/construction unit such as guardrail, gore areas, etc.?
3. What is your experience regarding VMS longevity/effectiveness?
4. What is your experience regarding ease of installation, repair, replacement, etc.?
5. What is your experience using VMSs for new and retrofit applications for ease of installation, worker safety, etc.?
6. Other issues?
7. What kind of guidance would you like to see in an interactive tool?

The only DOT interviewed that acknowledged familiarity with or use of the AASHTO *Guidelines for Vegetation Management* was Caltrans.

CALIFORNIA DEPARTMENT OF TRANSPORTATION

Caltrans has many years of experience in using non-herbicide VMSs. Caltrans has used a variety of materials and products, some with great success and others that have not performed well.

The four products deemed most successful are:

- Concrete
- Fiber weed mats
- Rubber weed mats
- Asphalt composite

Caltrans adopted standards for concrete, fiber weed mats, and rubber weed mats. Further experience with asphalt composite is needed before adopting as a standard, but the results are promising. In addition to these four materials, Caltrans now uses Styrofoam inserts as an option for leave-out areas. Leave-outs are required for rigid pavements.

Caltrans finds that tucking the leading edge of the fiber weed mats in the asphalt edge of pavement during initial installation leaves a clean edge with fewer problems. Experience with the rubber weed mat showed that the product needs to be at least 0.5 inches thick for best performance. Problems associated with the mats are damage and dislodging during roadside maintenance activities such as snow removal and storage. In terms of effective longevity, Caltrans installed fiber weed mat in the northern part of the state in 1997, and the material is still in place and effective. Rubber weed mat was installed in 2004 and has not shown problems. As with other VMSs, vegetation will try to grow over and around the weed mats and requires occasional maintenance.

The asphalt composite material is inexpensive, easy to install, and appropriate for new construction and retrofit applications. The key to success for this product is proper surface preparation. All vegetation and debris need to be removed and the surface compacted. Improperly prepared surfaces containing existing rock or other debris will allow vegetation to grow through the applied material. Also, the proper thickness is required.

A few other VMSs were tried, and a brief note on their performance includes:

- CRMCrete is comprised of concrete with recycled scrap tire crumb rubber as aggregate. The use of CRMCrete is expected to lower costs, increase durability, reduce worker roadside exposure, and provide alternatives for disposal of scrap tire rubber. Caltrans used CRMCrete at guardrail locations.
- Truck bed liner sprayed on the soil surface was expensive and had shadow areas where vegetation could grow.
- Spray expanding foam worked well for controlling weeds but was aesthetically unappealing and had issues with rodent infestations.
- Loose ground rubber and tire rubber chunks were not effective.
- Glued crumb rubber mats did not perform well.
- Herbicide-treated geosynthetics did not perform well.
- Flexible cement-impregnated fabric that hardens when hydrated to form a thin, durable concrete layer has been used in limited locations.

IDAHO TRANSPORTATION DEPARTMENT

The Idaho Transportation Department (ITD) stated that it does not use conventional VMSs regularly. ITD referred to its *Operations Manual* (ITD 2015) and *Best Management Practices (BMP) Manual* (ITD 2014) for standard practices. ITD's most used method relating to VMSs is the use of low-growing vegetation in areas where limited vegetation is desired. The areas adjacent to and underneath most roadside appurtenances are generally managed using mowers and weed eaters. Often in more rural areas, the vegetation not cut by mowers is left in place around the roadside appurtenance, post, etc. More urbanized areas may receive a greater level of maintenance. The use of low-growing vegetation at locations generally using a pervious VMS is viewed as advantageous for its green infrastructure-related benefits.

ITD uses soil sterilant in some areas that require no vegetation. Gravel may be used at the edge of pavement to control vegetation and to minimize the spread of fire. ITD has used rubber mats as a VMS; however, ITD found rubber mats to be problematic to install and replace in areas such as guardrail. The mats were time consuming to install, whether new construction or as a retrofit application.

ITD expressed an interest in VMS guidance regarding appropriate installation locations, maintenance issues and requirements, and effective longevity.

RHODE ISLAND DEPARTMENT OF TRANSPORTATION

The Rhode Island Department of Transportation (RIDOT) referred to its *Standard Specifications for Road and Bridge Construction*, “Section 213—Placement of Millings beneath Guardrail” (RIDOT 2018). This specification calls for recycled asphalt millings to be used as a VMS underneath guardrail. This is RIDOT’s most used VMS. Asphalt millings are also used at the edge of pavement. RIDOT stated that the asphalt millings are easy to install in new construction, repair, and retrofit applications. According to RIDOT, the most frequently seen problem is improper installation. RIDOT’s specification calls for the following:

- Millings to consist of bituminous material removed during cold planing operations and ground or crushed such that 100 percent of the material passes a 1-inch sieve
- Millings placed at all guardrail locations less than 2 feet from the edge of the existing pavement, or as indicated on the plans and/or as directed by the engineer
- Grade beneath the guardrail such that the finished surface of the millings is flush with the bituminous berm or edge of pavement
- Millings placed to a point 1 foot behind the guardrail post and shaped, compacted, and sloped to drain away from the pavement

RIDOT stated that some contractors do not compact the asphalt millings as the specification requires. According to RIDOT, compaction is critical to the performance and longevity of the VMS. The compaction process is more readily accomplished when RIDOT personnel conduct the installation process.

Another VMS used by RIDOT is organic wood mulch obtained through clearing and grubbing operations on the roadside. The chipped wood is spread onto areas to control vegetation. Effectiveness and longevity are less than the asphalt millings because the mulch decomposes and can easily be dislodged.

RIDOT requested that the interactive guidance tool be intuitive. Experience with other such tools showed them to be too complicated and/or more troublesome than just finding the desired information through other sources.

TEXAS DEPARTMENT OF TRANSPORTATION

TxDOT referred to its *Metal Beam Guard Fence (Mow Strip)* MBGF(MS)-19 (TxDOT 2019) that calls for the use of a reinforced concrete or asphalt pavement mow strip with an 18-inch by 18-inch or 18-inch-diameter minimum leave-out. Prior experience using VMSs includes vegetation mats and herbicide mats and tiles. These products had limited success. They were expensive to install and did not have reasonably effective longevity relative to the cost of installation and maintenance. TxDOT now uses only concrete and asphalt materials in locations needing VMSs because it did not find enough success with other applications to warrant their use.

CHAPTER 5. CONCLUSIONS

Controlling vegetation in critical areas has historically involved the use of mechanical methods, such as mowing and trimming, and chemical treatments using herbicides. These can create safety hazards for the traveling public and maintenance personnel. There is a growing body of research and project implementation regarding the use of VMSs. While the industry has emerging products, few studies have been conducted on product performance as it relates to non-herbicide, long-term VMSs. Many DOT implementation and/or demonstration projects using new techniques and/or products are conducted internally and may not be made publicly available through typical website searches.

SELECTING A VMS

As mentioned previously, VMSs can be categorized into three basic categories: impervious surfaces, pervious surfaces, and select vegetation establishment. Impervious surfaces are designed to cover the designated area, not provide a growth medium for plant materials, and minimize maintenance activities adjacent to the travel lanes. While impervious types of VMSs are very effective, they can be more expensive to install; however, these VMSs require minimal maintenance, have a low life cycle cost, and have high effective longevity. The most used VMSs are some types of concrete and asphalt. Pervious surface VMSs accomplish the same as impervious; however, these VMSs allow for stormwater infiltration. Select vegetation establishment consists of using low-growing, native non-irrigated, and/or ornamental irrigated vegetation. These plant materials are chosen for their ability to out-compete weeds and minimize unwanted vegetation. All VMSs are subject to some sort of maintenance. While impervious and pervious surface VMSs prohibit plant growth through the material, they are subject to windblown soil that provides a medium for weed growth.

To provide state DOTs with more detailed information on VMSs and guide the selection of a specific strategy, the research team developed an Interactive Selection Tool. The tool offers guidelines on non-herbicide, long-term VMSs for roadsides and roadside appurtenances. The development of the Interactive Selection Tool was based on the information collected from the literature review, survey of practice, and follow-up interviews with select DOTs. This tool employs a decision algorithm to advise the user of the appropriate VMS treatments for the specific conditions. The tool can be downloaded from https://www.dropbox.com/s/coqfcnab92gvfx5/NCHRP%20W350_Selection%20Tool.zip?dl=0.

A user guide with step-by-step instructions on how to download and use the Interactive Selection Tool is provided in Appendix B (page B-2). The instructions for using the tool are also available in the tool folder when downloaded.

The Interactive Selection Tool provides identification and guidelines for the selection of non-herbicide, long-term VMSs for roadsides and roadside appurtenances. The VMSs identified and presented *do not* present specific design guidance for highway safety appurtenances, nor are they a substitute for any other highway design practice. The user should refer to the RDG, MASH testing, and any specific state DOT practices for warrants, proper placement, and maintenance of roadside safety appurtenances when applying these VMSs (AASHTO 2011b, 2016). In addition, before applying any of the described techniques on a proprietary roadside safety hardware device (e.g., guardrail terminal, crash cushion, or breakaway sign support), the manufacturer should be contacted to discuss the potential for the treatment to adversely affect the performance of the manufacturer's safety hardware device. VMSs applied in and around highway safety appurtenances should consider their effect on the performance of everything in the highway design environment. If a VMS is thought to possibly influence the performance of a highway safety appurtenance, then consideration should be given to crash testing the VMS and safety appurtenance together as a system.

The various categories of roadside safety appurtenances were discussed regarding the application of VMSs. The use of VMSs around rigid barriers, such as concrete barriers, is acceptable provided the treatment does not extend above the pavement surface and does not alter the height of the barrier. Conversely, the semi-rigid barrier does displace and/or rotate when impacted, and those specific characteristics should not be altered. A VMS applied to a portable semi-rigid concrete barrier should not alter the barrier installation's ability to displace laterally or rotate upon impact. Metal beam guardrail/guard fence (e.g., W-beam and thrie beam) can be configured as a semi-rigid or flexible longitudinal barrier. For strong post systems (e.g., guardrail installations, including guardrail transitions and guardrail end treatments), the proper lateral displacement and rotation of the posts reduces the chances of rail rupture and is critical to the proper operation of the barrier when impacted. For these systems, the rotation of the strong post should not be impeded or restrained by the VMS. MASH-tested mow strip configurations with properly designed leave-outs around the posts are one form of VMS for these systems. Certain approved backfill materials such as low-strength grout can be used in the leave-outs to control vegetation in those areas. Posts in high-tension cable barrier and other weak post (e.g., S3x5.7 steel post) guardrail systems do not need a leave-out in the mow strip. Weak post barrier systems do not rely on the displacement and rotation of the post like a strong post system does to perform successfully. During an impact, weak posts bend at or near the groundline and thus may be more rigidly constrained by the applied VMS.

MASH-tested terminals and crash cushions are all proprietary to date. As previously presented, before applying any of the VMS techniques described herein to a proprietary roadside safety hardware device (e.g., guardrail terminal, crash cushion, or breakaway sign support), the manufacturer should be contacted to discuss if and how the treatment might adversely affect the performance of the manufacturer's safety hardware device.

When applying a VMS to a support structure (e.g., sign or luminaire support), the designer must avoid interfering with the activation and release of the system for it to perform properly. This means keeping the applied VMS from obstructing the displacement of bolts or slip plates from slip bases, being in the path of the rotating support after it releases from its foundation or anchor, or significantly altering the impact height of the errant vehicle by altering the effective ground height around the structure or the vehicle approach to the structure.

VMS TREATMENT SELECTION USING INTERACTIVE SELECTION TOOL

There are numerous considerations in choosing a VMS. Each site has specific needs that include the cost of initial installation, maintenance, and repair. Other considerations are the overall life cycle cost, suitability as new construction or retrofit, and effective longevity. The Interactive

Selection Tool requires three categories of user input with dropdown menus based on site-specific conditions:

- VMS location
  - Cable barrier
  - Support posts and poles
  - Edge of pavement
  - Gore/median
  - Guardrail
  - Mow edge
  - Slope/embankment
- Level of aesthetics
  - Standard
  - High
- Construction type
  - New construction
  - Retrofit

VMS Location

The VMS locations (i.e., cable barrier, support posts and poles, edge of pavement, gore/median, guardrail, mow edge, and slope/embankment) were chosen for use in the Interactive Selection Tool because they stand out in the literature, survey, and DOT documents as the most common areas where VMSs are used. Other areas needing VMSs are placed into each of these categories because they did not have any significant difference in use.

Level of Aesthetics

The site location and context may be a factor in choosing a VMS. Considerations include whether the site is urban, suburban, or rural and the adjacent land use such as residential, commercial, industrial, or agricultural. This choice is indicated by the level of aesthetics and has a rating of high or standard. A high rating is generally indicative of an urban or suburban location or other locations where stakeholders expect a greater level of aesthetic treatment. An example of this might be a gore/median or slope in a highly urbanized area or city entrance location. A standard rating may apply to less visible uses of VMSs such as under a median cable barrier in a rural location. The Interactive Selection Tool will select VMSs typically used for the given user criteria. However, this does not mean that a VMS selection with a standard aesthetic rating cannot be used in high-aesthetic locations.

From this input, the Interactive Selection Tool will provide VMS choices based on user input. Figure 30 shows a typical result.

Figure 30. Selection Tool Input Result Example.

Information Sheets

From these selections, the Interactive Selection Tool will generate commonly used VMS treatments given the user inputs. If using with a strong post guardrail, refer to the "Strong Post Guardrail Use with Rigid VMS Materials" information sheet for leave-out compliance requirements. This information sheet provides critical information regarding the interaction of rigid materials and safety appurtenances. For more information regarding the specific VMS, the user can select the imbedded link "Information Sheet" or the photo, which will bring up an information sheet (found in Appendix C) regarding specifics about the selected VMS that include:

- Relative costs
    - Installation
    - Life cycle
    - Maintenance
    - Repair
- Effective longevity
- Level of difficulty
    - Installation
    - Repair
    - Maintenance
    - Retrofit

Relative Initial Cost

The Interactive Selection Tool includes information on cost ranges for each VMS. Identifying costs for a specific material used as a VMS by DOTs was difficult because the VMS is typically integral to a larger construction project. Costs for VMSs vary greatly based on quantity, availability, and location. Cost ranges are relative to other VMSs and based on costs associated with the specific VMS per Caltrans and TxDOT pricing shown in Table 2. In the tool, the cost ranges are as follows:

- High installation cost is \$85 yd^2 or greater.
- Moderate installation cost is between \$50 and \$85 yd^2.
- Low installation cost is up to \$50 yd^2.

Effective Longevity

Effective longevity is determined by the anticipated material life cycle and the level of maintenance routinely required of the specific VMS:

- High effective longevity is at least 10 years.
- Moderate effective longevity is 3 to 10 years.
- Low effective longevity is up 3 years.

Level of Difficulty

The safety of maintenance personnel is directly related to the level of difficulty and/or time requirements for material installation, maintenance, and repair. Workers' safety is greatly affected by increased exposure to traffic and other roadside hazards. The need for prolonged traffic controls necessary to complete the required tasks is important. Therefore, each VMS receives a level-of-difficulty rating of low, moderate, or high. This is not only indicative of the specific VMS material characteristics; it also includes a relative level of worker safety and exposure during installation, maintenance, and repair.

Advantages/Limitations/Common Problems

The information sheets also list the advantages, limitations, and common problems of each included VMS treatment. These may be considerations such as installation uses, typical maintenance, equipment/practices, or AASHTO RDG and MASH compliance requirements for leave-outs. Common problems may be displacement by errant vehicles and maintenance equipment.

VMSs Included in Tool

The Interactive Selection Tool includes VMSs found in use by DOTs from the survey results, literature, and DOT websites and documents. Many of the VMSs were either minimally used or are not being used by DOTs per survey results. However, all the VMSs included in the tool were used by at least three of the survey respondents and/or are found in various DOT documents and websites. The VMSs included in the tool are listed below. Appendix C provides information sheets on each VMS. These information sheets are also included in the Interactive Selection Tool. A downloadable table of the included VMSs can be downloaded using the following link. To open/run the Tool click on the link below and follow the directions in "How to Run the Tool" on page B-2.

Impervious Surface VMSs

Impervious surface VMSs include the following:

- Minor concrete pavement
- Crumb Rubber Modified Concrete

- Standard concrete pavement
- Patterned concrete pavement
- Asphalt concrete pavement
- Stamped asphalt pavement
- Asphalt composite
- Rock blanket
- Rubber weed mat

Pervious Surface VMSs

Pervious surface VMSs include the following:

- Modular paving units (may be pervious depending on application)
- Weed control fiber mat
- Glass cullet
- Gravel mulch
- Rock slope protection
- Organic mulch
- Recycled asphalt millings
- Aggregate base

Selected Vegetation Establishment VMSs

Selected vegetation establishment VMSs include the following:

- Irrigated ornamental vegetation
- Native and non-irrigated vegetation

Alternative and Innovative VMSs

A search of the literature and DOT documents and websites found little in the way of innovative practices or new materials. Many products and materials are of the typical VMS types but with different product names. One VMS noted as tried by Caltrans is a GCCM. This mat is a flexible, concrete-filled geotextile that hardens on hydration to form a thin, durable, waterproof, and low-carbon concrete layer—essentially concrete on a roll. This material may require leave-outs to maintain safety performance of roadside appurtenances. GCCM products show potential for use as VMSs, but there are no weed control performance data for this use; Caltrans has used one of these products in limited locations. Although experience with this VMS is very limited, an information sheet on GCCMs is included in Appendix C.

FURTHER ADDITIONAL UPDATES TO AASHTO *GUIDELINES FOR VEGETATION MANAGEMENT*

There is an opportunity for future research to advance transportation agencies' knowledge regarding non-herbicide, long-term VMSs. This project also identified several knowledge gaps and needed updates/additions to the AASHTO *Guidelines for Vegetation Management*.

Resilience

Transportation resilience is the ability of a transportation system to function at an acceptable rate in the event of extreme weather events, major crashes, and equipment or infrastructure failures. Quick recovery of a system is critical to avoid long-term effects. State DOTs need information on VMSs that can increase resilience of transportation facilities and the transportation system.

Pollinators

In June 2014, the White House issued the PM, “Creating a Federal Strategy to Promote the Health of Honeybees and Other Pollinators.” The PM directs federal agencies to take additional steps to improve habitat for pollinators, including honeybees, native bees, birds, bats, and butterflies—critical contributors to our nation’s economy, food system, and environmental health. With millions of acres of highway roadsides, state and local transportation agencies own or control land with the ability to conserve and/or create important habitat corridors that link otherwise fragmented pollinator habitat. State DOTs need information on how to update their vegetation management policies, practices, and standards to align with the PM on pollinators.

Herbicides

Herbicide-resistant weeds are becoming problematic for roadside vegetation managers. Herbicide manufacturers are changing the basic chemistry to combat resistance. This is becoming more and more difficult because some chemicals are being deleted from the roadside maintenance arsenal. The U.S. Department of Agriculture has taken over all aspects of herbicide control (i.e., licensing, training, etc.). State DOTs need information on how to respond to herbicide resistance and the current regulatory environment.

Managed Succession

Many DOTs are implementing more non-mow or reduced-mow areas within their ROW due to the cost, safety, and environmental benefits of managed succession of roadside vegetation outside the safety clear zone. Many of the benefits fall under ESs. These ES benefits include ecosystem diversity, stormwater quantity and quality management, carbon sequestration, erosion control, pollinator corridor development, wildlife habitat, and aesthetics. State DOTs need information on how managed succession can be used to advance environmental benefits, deliver ES, and better manage roadside vegetation.

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APPENDIX A: TXDOT VEGETATION MANAGEMENT STRATEGY INSTALLATION

Anti-vegetation Tile Demonstration Project guardrail installation in Portland, Texas, in August 2004.

Figure A1. TxDOT Demonstration Installation (TxDOT 2012).

APPENDIX B: INTERACTIVE SELECTION TOOL USER MANUAL

NCHRP 14-41 Interactive Selection Tool User Manual

This user manual provides guidance on the use of the interactive tool developed for NCHRP 14-41 Long-Term Vegetation Management Strategies for Roadsides and Roadside Appurtenances. This tool employs a decision algorithm to advise the user of the appropriate VMSs for specific conditions. The tool's interactive decision rules are in a self-contained folder format that can be downloaded using the following link. To open/run the Tool click on the link below and follow the directions in "How to Run the Tool" at https://www.dropbox.com/s/coqfcnab92gvfx5/NCHRP%20W350_Selection%20Tool.zip?dl=0.

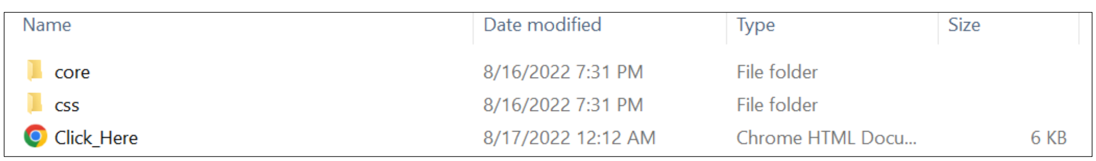
HOW TO RUN THE TOOL

To run the NCHRP 14-41 tool using the zipped, self-contained folder, please follow these steps:

1. Download the folder by selecting the folder and clicking on the download tab.

Note: Downloading may take a few minutes based on internet speeds.

2. Go to the folder in which the file has been downloaded. The downloaded file will be a zipped file. You need to **unzip the folder** (extract files) to run the tool. After unzipping, the folder will show the following items (two folders and 'Click_Here' html file).



Name	Date modified	Type	Size
core	8/16/2022 7:31 PM	File folder	
css	8/16/2022 7:31 PM	File folder	
Click_Here	8/17/2022 12:12 AM	Chrome HTML Docu...	6 KB

3. Click "Click_Here" to open the tool (it will automatically open in a web browser such as Chrome).

Note: The user needs to download the zipped folder and unzip the folder to run the tool.

INTERFACE

Figure B1 shows the interface of the opening page for the interactive tool. The user clicks "Click_Here.htm" in the "NCHRP14_41Tool" folder. Clicking on "Click_Here.htm" opens the interactive tool in a web browser (which will depend on the browser selection of the user). The source code and algorithms are stored in two other folders ("core" and "css," respectively). The user does not need to explore these folders to run the tool.

Figure B1. Interface of the NCHRP 14-41 Tool Opening Page.

The web interface has four different tabs:

- Home (the interface shown in Figure B1)
- Selection Tool (users can go to this tab by clicking on it or by clicking on "Get Started" on the interface page)
- Non-Herbicide VMS
- Additional Resources

GETTING STARTED

This section describes the basic information needed to perform permanent vegetation control treatment selection. Figure B2 shows the interface of the "Non-Herbicide VMS Selection Tool." This page contains two tabs ("General Introduction" and "Tool Instructions"). The "General Introduction" tab provides a brief overview of the purpose of this tool. The "Tool Instructions" tab provides a description of this tool.

The main tool has the following options:

- **VMS Location:** a dropdown panel including cable barrier, support posts and poles, edge of pavement, gore/median, guardrail, mow edge, and slope/embankment
- **Level of Aesthetics:** a dropdown panel including standard and high
- **Construction Type:** a dropdown panel including new construction and retrofit

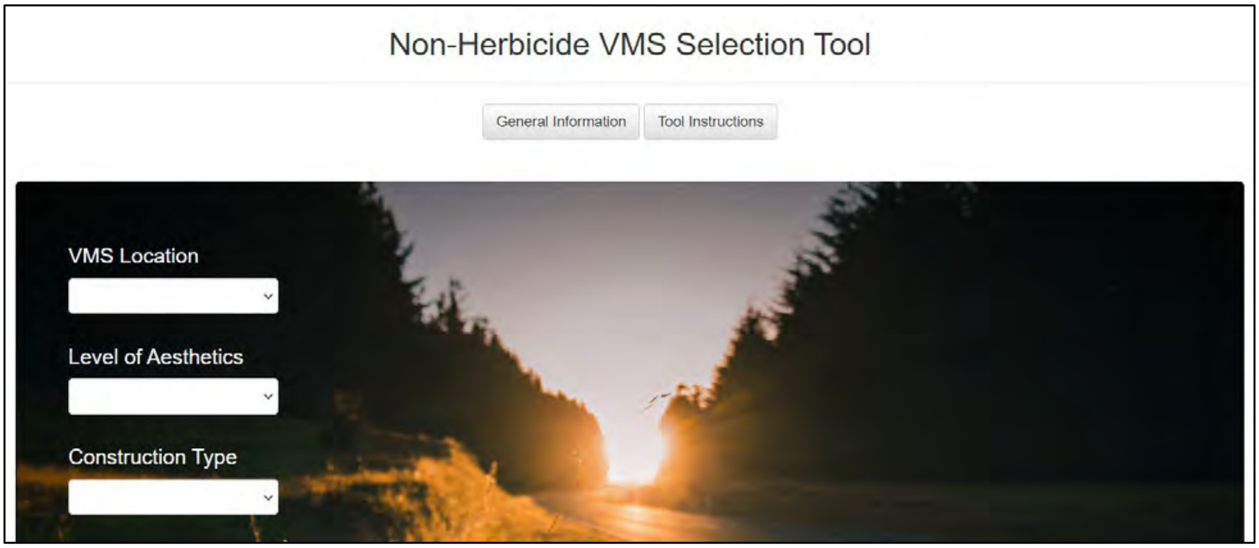


Figure B2. Non-Herbicide VMS Selection Tool.

SELECT OPTIONS

A list of VMSs will be populated for different combination options. Figure B3 shows an example treatment (with its synopsis) that is generated based on some selection criteria.

Figure B3. Treatment: Patterned Concrete Pavement.

Example 1: What retrofit non-herbicide VMS applications are recommended at the edge of pavement in an urban location?

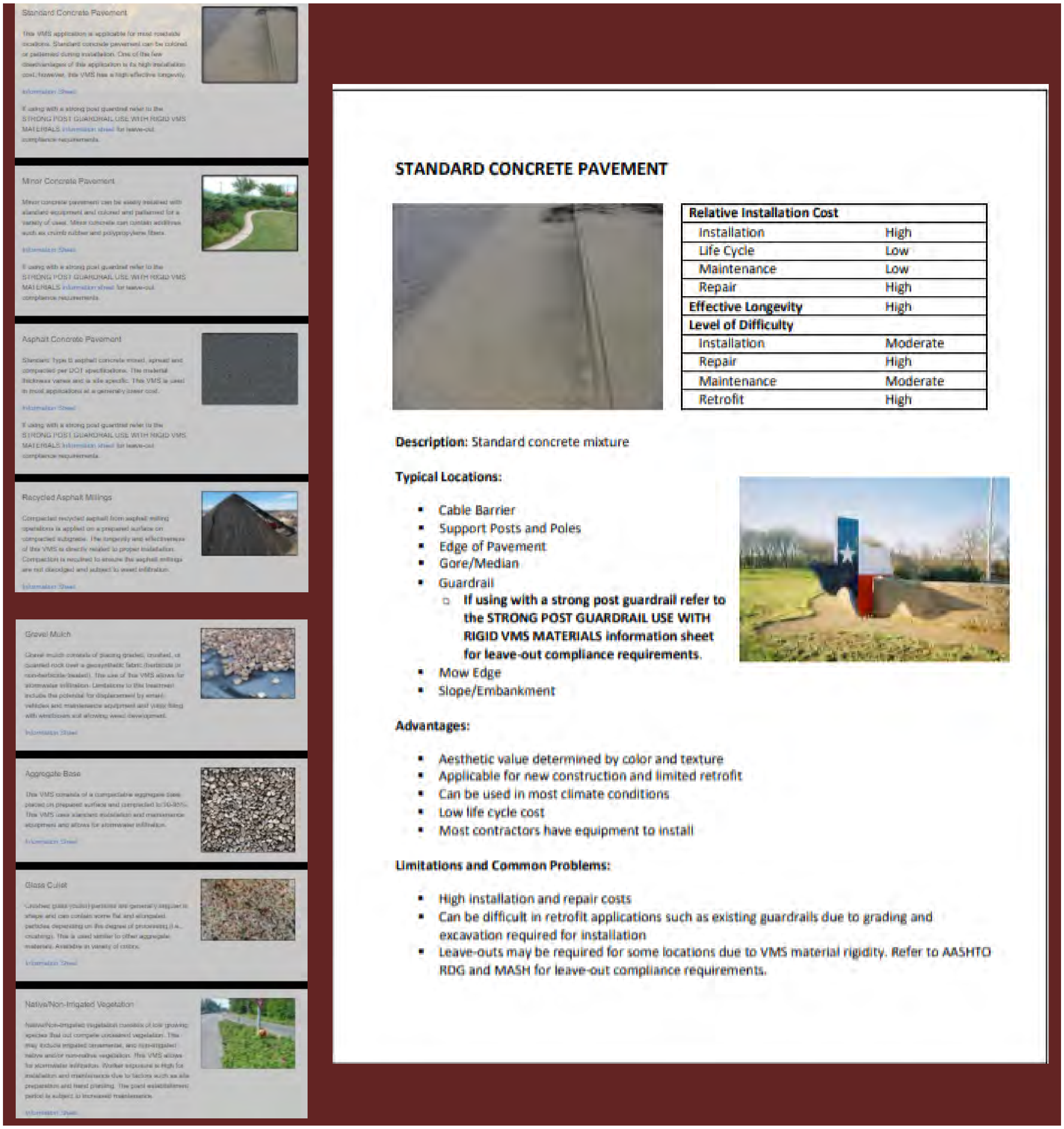
To determine the appropriate VMS, the user needs to select the following options:

- **VMS Location:** Edge of Pavement
- **Level of Aesthetics:** Standard
- **Construction Type:** Retrofit

Twenty VMS applications will be populated from this selection criteria (see Figure B4a):

- Aggregate Base
- Asphalt Composite
- Asphalt Concrete Pavement
- Crumb Rubber Modified Concrete
- GCCM
- Glass Cullet
- Gravel Mulch
- Irrigated Ornamental Vegetation
- Minor Concrete Pavement
- Modular Paving Units
- Native and Non-Irrigated Vegetation
- Organic Mulch
- Patterned Concrete Pavement
- Recycled Asphalt Millings
- Rock Blanket
- Rock Slope Protection
- Rubber Weed Mat
- Stamped Asphalt Pavement
- Standard Concrete Pavement
- Weed Control Fiber Mat

To get additional information on these treatments, the user clicks “Information Sheet.” For example, a PDF file in a separate browser page will be populated by clicking “Information Sheet” from “Standard Concrete Pavement.”



STANDARD CONCRETE PAVEMENT

Relative Installation Cost	
Installation	High
Life Cycle	Low
Maintenance	Low
Repair	High
Effective Longevity	High
Level of Difficulty	
Installation	Moderate
Repair	High
Maintenance	Moderate
Retrofit	High

Description: Standard concrete mixture

Typical Locations:

- Cable Barrier
- Support Posts and Poles
- Edge of Pavement
- Gore/Median
- Guardrail
  - **If using with a strong post guardrail refer to the STRONG POST GUARDRAIL USE WITH RIGID VMS MATERIALS information sheet for leave-out compliance requirements.**
- Mow Edge
- Slope/Embankment

Advantages:

- Aesthetic value determined by color and texture
- Applicable for new construction and limited retrofit
- Can be used in most climate conditions
- Low life cycle cost
- Most contractors have equipment to install

Limitations and Common Problems:

- High installation and repair costs
- Can be difficult in retrofit applications such as existing guardrails due to grading and excavation required for installation
- Leave-outs may be required for some locations due to VMS material rigidity. Refer to AASHTO RDG and MASH for leave-out compliance requirements.

(a) VMS populated for Example 1

(b) Information Sheet PDF for a VMS

Figure B4. Example 1.

NON-HERBICIDE VMSS AND ADDITIONAL RESOURCES

The other two tabs (“Non-Herbicide VMS” and “Additional Resources”) provide additional contexts of this tool. The “Non-Herbicide VMS” tab provides a tabular format of all VMSs (see Figure B5). The “Additional Resources” tab provides some relevant studies with hyperlinks. Clicking on the images opens the information sheet in a new tab. The spreadsheet can also be download as a PDF document by clicking “Click here to download the table.”

Long-Term VMS for Roadsides and Roadside Appurtenances

Click here to download the table

Treatments	Image	Applications	Aesthetics	Relative Costs				Requires Leave Out	
				Installation	Life-cycle	Maintenance	Repair		Installation
Standard Concrete Pavement		GR, SP, GM SE, EP, ME, CB	H, S	High	Low	Low	High	SPG	Moderate
Minor Concrete Pavement		GR, SP, GM SE, ME, CB	H, S	Moderate/High	Low	Low	High	SPG	Moderate

Figure B5. Non-Herbicide VMS Tab.

APPENDIX C: INTERACTIVE SELECTION TOOL INFORMATION SHEETS

AGGREGATE BASE

Relative Costs	
Installation	Moderate
Life Cycle	Moderate
Maintenance	Low
Repair	Low
Effective Longevity	Moderate
Level of Difficulty	
Installation	Low
Repair	Low
Maintenance	Low
Retrofit	Low

Description: Compactable aggregate base placed on prepared surface and compacted to 90–5%

Typical Locations:

- Cable barrier
- Support posts and poles
- Edge of pavement
- Gore/median
- Guardrail
- Mow edge
- Slope/embankment

Advantages:

- Low-cost treatment applicable for new construction and retrofit locations
- Aesthetic value determined by aggregate color and type
- Can be used in most climate conditions
- Uses standard installation/maintenance equipment
- Allows for storm water infiltration

Limitations and Common Problems:

- May not be applicable in areas with snow removal equipment and snow storage
- Displacement by errant vehicles and maintenance equipment
- May require spot herbicide treatment and re-compaction

ASPHALT COMPOSITE

Relative Costs	
Installation	Low
Life Cycle	Low
Maintenance	Low
Repair	Low
Effective Longevity	High
Level of Difficulty	
Installation	Low
Repair	Low
Maintenance	Low
Retrofit	Low

Description: Single-step, seamless, cold-spray-applied asphalt emulsion reinforced with fiberglass strands. Site preparation consists of general grubbing, compaction, and application of pre-emergent herbicide to provide a relatively smooth surface to place the product.

Typical Locations:

- Cable barrier
- Support posts and poles
- Gore/median
- Guardrail
- Mow edge

Advantages:

- Flexible, durable, and solid barrier
- Adheres to asphalt, concrete, wood, and metal
- Installed using typical maintenance equipment/practices
- Low life cycle costs
- Low cost and easy installation and repairs
- Applicable for new construction and retrofit locations
- Seamless installation to reduce vegetation encroachment at seams
- Rapid, single-step, high-rate application minimizes lane closure and worker exposure
- Safe for use near water runoff areas
- Can withstand machine traffic

Limitations and Common Problems:

- Requires installation temperature >50°
- Requires leave-out

ASPHALT CONCRETE PAVEMENT

Relative Costs	
Installation	Low/Moderate
Life Cycle	Moderate
Maintenance	Moderate
Repair	Moderate
Effective Longevity	Moderate
Level of Difficulty	
Installation	Moderate
Repair	Moderate
Maintenance	Moderate
Retrofit	Moderate/High

Description: Standard Type B asphalt concrete mixed, spread, and compacted per DOT specifications. Material thickness varies and is site specific.

Typical Locations:

- Cable barrier
- Support posts and poles
- Edge of pavement
- Gore/median
- Guardrail
  If using with a strong post guardrail, refer to the STRONG POST GUARDRAIL USE WITH RIGID VMS MATERIALS information sheet for examples of recently tested designs with leave-outs.
- Mow edge

Advantages:

- Generally lower installation cost
- Applicable for new construction and uses readily available material
- Most contractors and DOTs have equipment and training for installation

Limitations and Common Problems:

- Leave-outs may be required due to VMS material rigidity. Refer to AASHTO RDG, MASH, recent research, and/or other guidelines to determine leave-out compliance requirements.
- Restricted work area may limit use of asphalt concrete installation equipment
- Lower installation cost but high life cycle cost when compared to minor concrete
- Material degrades in areas not receiving regular compaction from traffic, allowing weed establishment
- Small batch base materials may prove problematic and expensive

CRUMB RUBBER MODIFIED CONCRETE

Relative Costs	
Installation	Low/Moderate
Life Cycle	Low
Maintenance	Low
Repair	High
Effective Longevity	High
Level of Difficulty	
Installation	Low/Moderate
Repair	High
Maintenance	Moderate
Retrofit	High

Description: Crumb rubber modified concrete (CRMCrete) is a concrete-based product using a slurry blend of recycled scrap tire crumb rubber material and homopolymer polypropylene high-performance reinforcing fibers. CRMCrete is installed like concrete and can be used with color and texture for increased aesthetic value. This product is comparable in use and characteristics to minor concrete.

Typical Applications:

- Cable barrier
- Support posts and poles
- Edge of pavement
- Gore/median
- Guardrail
  If using with a strong post guardrail, refer to the STRONG POST GUARDRAIL USE WITH RIGID VMS MATERIALS information sheet for examples of recently tested designs with leave-outs.
- Mow edge

Advantages:

- Color can be added
- Formwork is not always necessary
- Higher daily production rates—faster than other surface treatments
- Easy installation
- Uses standard equipment and concrete mixes
- Uses recycled tire rubber material

Limitations and Common Problems:

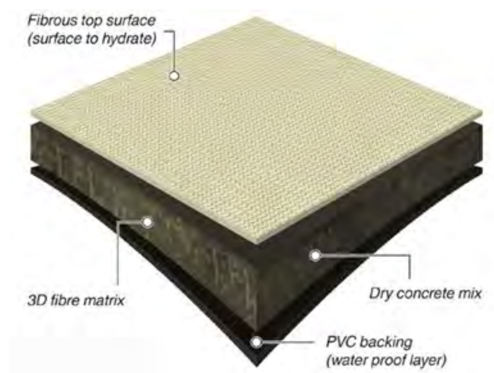
- Consistency of mix may limit its use on slopes
- Limited history of maintainability and life cycle costs
- Repairs are difficult to match to the original color if you use a concrete stain
- Leave-outs may be required due to VMS material rigidity. Refer to AASHTO RDG, MASH, recent research, and/or other guidelines to determine leave-out compliance requirements.

GEOSYNTHETIC CEMENTITIOUS COMPOSITE MATS

Relative Costs	
Installation	N/A
Life Cycle	N/A
Maintenance	N/A
Repair	N/A
Effective Longevity	N/A
Level of Difficulty	
Installation	Low
Repair	Low
Maintenance	N/A
Retrofit	Low

Description: GCCM is a flexible cement-impregnated fabric that hardens when hydrated to form a thin, durable concrete layer. This material has different proprietary name such as Concrete Cloth™ and Concrete Canvas®. This VMS consists of a dry concrete mix, reinforcing fiber matrix, fabric top surface, and poly vinyl chloride (PVC) bottom coating for waterproofing.

Typical Locations:



- Cable barrier
- Support posts and poles
- Gore/median
- Guardrail
  If using with a strong post guardrail, refer to the STRONG POST GUARDRAIL USE WITH RIGID VMS MATERIALS information sheet for examples of recently tested designs with leave-outs.
- Mow edge
- Slope/embankment

Advantages:

- Rapid and easy installation
- Product comes on a roll so no concrete mixing
- Waterproof and fireproof
- Flexible enough to allow material to conform to surface
- Unset material can be cut as necessary for given situation

Limitations and Common Problems:

- Leave-outs may be required due to VMS material rigidity. Refer to AASHTO RDG, MASH, recent research, and/or other guidelines to determine leave-out compliance requirements.
- **Limited available information regarding VMS interaction, long-term cost, performance, and maintenance as a VMS**

GLASS CULLET

Relative Costs	
Installation	Low
Life Cycle	Low
Maintenance	Low
Repair	Low
Effective Longevity	High
Level of Difficulty	
Installation	Low
Repair	Low
Maintenance	Low
Retrofit	Low

Description: Crushed glass (cullet) particles are generally angular in shape and can contain some flat and elongated particles depending on the degree of processing (i.e., crushing).

Typical Locations:

- Cable barrier
- Support posts and poles
- Edge of pavement
- Gore/median
- Guardrail

Advantages:

- Aesthetic qualities
- Works well for flat areas
- Does not decompose
- Wide variety of colors and sizes available
- Uses recycled material

Limitations and Common Problems:

- Not recommended for use on slopes
- Reflective—glare issue and reflects the underlayment
- Proper processing is required
- Supportive border may be necessary
- **Limited information regarding long-term cost, performance, and maintenance as a VMS**

GRAVEL MULCH

Relative Costs	
Installation	Low
Life Cycle	Low
Maintenance	Low
Repair	Low
Effective Longevity	Moderate
Level of Difficulty	
Installation	Low
Repair	Low
Maintenance	Low
Retrofit	Low

Description: Graded, crushed rock placed on geosynthetic fabric (herbicide or non-herbicide treated)

Typical Locations:

- Support posts and poles
- Edge of pavement
- Gore/median
- Slope/embankment

Advantages:

- Low-cost treatment for new construction and retrofit
- Aesthetic value determined by gravel color and texture
- Can be used in most climate conditions
- Uses standard installation/maintenance equipment
- Allows for storm water infiltration

Limitations and Common Problems:

- May not be applicable in areas with snow removal equipment and snow storage
- Displacement by errant vehicles and maintenance equipment
- Requires removal of windblown debris
- Subject to voids filling with windblown soil, allowing weed development
- Gravel should be placed approximately 1–2 inches thick. Finish grade of gravel should be equal to adjacent grade and flow lines.

IRRIGATED ORNAMENTAL VEGETATION

Relative Costs	
Installation	High
Life Cycle	Moderate/High
Maintenance	Moderate
Repair	Moderate
Effective Longevity	Moderate
Level of Difficulty*	
Installation	Moderate
Repair	Moderate
Maintenance	Moderate
Retrofit	Moderate

Description: Low-growing species that out-competes undesired vegetation. This may include native and/or non-native vegetation.

Typical Locations:

- Gore/median
- Slope/embankment

Advantages:

- High aesthetic value
- Uses standard installation/maintenance equipment
- Applicable for new construction and retrofit
- Allows for storm water infiltration
- Provides erosion control
- Out-competes weeds when established

Limitations and Common Problems:

- ***** Worker exposure is high for installation and maintenance
- Requires site preparation
- Plant establishment period subject to increased maintenance
- Costs subject to extent of landscape development
- Limited use in arid/semi-arid locations
- Limited use in areas subject to fire hazard
- Subject to climate effects
- Subject to damage and displacement from errant vehicles, wind, mowers, and snow removal equipment

MINOR CONCRETE PAVEMENT

Relative Costs	
Installation	Moderate/High
Life Cycle Cost	Low
Maintenance	Low
Repair	High
Effective Longevity	High
Level of Difficulty	
Installation	Moderate
Repair	High
Maintenance	Moderate
Retrofit	High

Description: Standard concrete that includes crumb rubber or polypropylene fibers

Typical Locations:

- Cable barrier
- Support posts and poles
- Edge of pavement
- Gore/median
- Guardrail
  If using with a strong post guardrail, refer to the STRONG POST GUARDRAIL USE WITH RIGID VMS MATERIALS information sheet for examples of recently tested designs with leave-outs.
- Mow edge
- Slope/embankment

Advantages:

- Comparable cost to standard concrete paving
- Easily installed with standard tools and equipment
- Aesthetic value determined by use of colors and patterns

Limitations and Common Problems:

- Leave-outs may be required due to VMS material rigidity. Refer to AASHTO RDG, MASH, recent research, and/or other guidelines to determine leave-out compliance requirements.
- Not recommended for retrofit locations such as existing guardrails due to grading and excavation required for installation

MODULAR PAVING UNITS

Relative Costs	
Installation	Moderate/High
Life cycle	Low
Maintenance	Low
Repair	Low
Effective Longevity	High
Level of Difficulty	
Installation*	Moderate/High
Repair	Low
Maintenance	Low
Retrofit	Moderate

Description: Generally concrete or brick paving units available in a variety of shapes, colors, and structural characteristics

Typical Locations:

- Support posts and poles
- Gore/median
- Mow edge
- Slope/embankment

Advantages:

- High aesthetic appeal—variety of colors and patterns
- Good for use in urban/high-visibility locations
- Applicable for new construction and retrofit
- Can be used in most climate conditions
- Most contractors have installation equipment
- Allows easy repairs and access to subsurface utilities
- Can be specified for pedestrian or vehicle traffic
- Used with or without mortar
- Can be set on impervious or pervious base

Limitations and Common Problems:

- * Worker exposure is high for installation
- Requires supportive edge
- Can be dislodged by heavy vehicle traffic
- Can be used under guardrail but not considered a typical location
- Subject to damage and displacement from errant vehicles, mowers, and snow removal equipment
- Subject to voids filling with windblown soil, allowing weed development
- Limited slope applications if not set in mortar
- Leave-outs may be required due to VMS material rigidity. Refer to AASHTO RDG, MASH, recent research, and/or other guidelines to determine leave-out compliance requirements.
- **If using with a strong post guardrail, refer to the STRONG POST GUARDRAIL USE WITH RIGID VMS MATERIALS information sheet for examples of recently tested designs with leave-outs.**

NATIVE AND NON-IRRIGATED VEGETATION

Relative Costs	
Installation	Low/Moderate
Life Cycle	Low/Moderate
Maintenance	Low/Moderate
Repair	Low/Moderate
Effective Longevity	Moderate
Level of Difficulty*	
Installation	Moderate
Repair	Moderate
Maintenance	Moderate
Retrofit	Moderate

Description: Low-growing species that out-compete undesired vegetation. This may include native and/or non-native vegetation.

Typical Locations:

- Cable barrier
- Edge of pavement
- Gore/median
- Guardrail
- Slope/embankment

Advantages:

- High aesthetic value
- Applicable for new construction and retrofit
- Uses standard installation/maintenance equipment
- Allows for storm water infiltration
- Provides erosion control
- Out-competes weeds when established

Limitations and Common Problems:

- *Worker exposure is high for installation and maintenance
- Requires site preparation
- Plant establishment period subject to increased maintenance
- Limited use in arid/semi-arid locations
- Limited use in areas subject to fire hazard
- Subject to climate effects
- Subject to damage and displacement from errant vehicles, wind, mowers, and snow removal equipment
- Subject to effects of winter operations

ORGANIC MULCH

Relative Costs	
Installation	Low
Life Cycle	Moderate/High
Maintenance	Moderate
Repair	Low
Effective Longevity	Low
Level of Difficulty	
Installation	Low
Repair	Low
Maintenance	Low
Retrofit	Low

Description: Consists of surface-applied, mulched recycled materials such as chipped wood and bark usually placed on geosynthetic fabric (herbicide or non-herbicide treated)

Typical Locations:

- Gore/median
- Slope/embankment

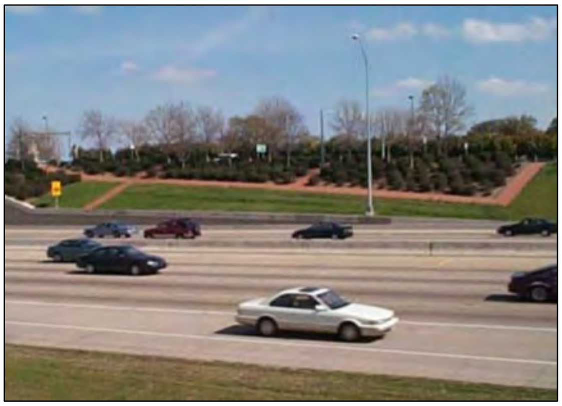
Advantages:

- Can be used in most climate conditions
- Uses standard installation/maintenance equipment
- Aesthetic value determined by color and texture
- Applicable for new construction and retrofit
- Allows for storm water infiltration
- Provides erosion control
- Uses recycled materials

Limitations and Common Problems:

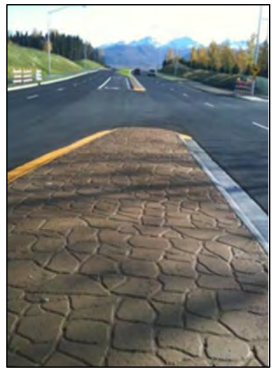
- Limited longevity—2 to 3 years
- A 4-inch layer mulch depth should be reapplied every 2 to 3 years
- Subject to degradation
- May require reapplication
- May not be suitable for slopes greater than 1V:3H without tackifier
- Not suitable in areas subject to fire hazard
- Subject to damage and displacement from errant vehicles, wind, mowers, and snow removal equipment
- Subject to voids filling with windblown soil, allowing weed development

PATTERNED CONCRETE PAVEMENT



Relative Costs	
Installation	High
Life Cycle Cost	Moderate
Maintenance	Moderate/High
Repair	High
Effective Longevity	High
Level of Difficulty	
Installation	High
Repair	High
Maintenance	Moderate
Retrofit	High

Description: Standard concrete mixture using color additive and stamped pattern



Typical Locations:

- Cable barrier
- Support posts and poles
- Edge of pavement
- Gore/median
- Guardrail
  If using with a strong post guardrail, refer to the STRONG POST GUARDRAIL USE WITH RIGID VMS MATERIALS information sheet for examples of recently tested designs with leave-outs.
- Mow edge
- Slope/embankment

Advantages:

- High aesthetic appeal—variety of colors and patterns
- Good for use in urban/high-visibility locations
- Can be used in most climate conditions
- Applicable for new construction and limited retrofit
- Low life cycle cost
- Most contractors have equipment to install

Limitations and Common Problems:

- High installation and repair costs—may be difficult to match color and pattern for repair
- Not recommended for retrofit locations such as existing guardrails
- Leave-outs may be required due to VMS material rigidity. Refer to AASHTO RDG, MASH, recent research, and/or other guidelines to determine leave-out compliance requirements.
- May be damaged by snow removal equipment
- Subject to voids filling with windblown soil, allowing weed development

RECYCLED ASPHALT MILLINGS

Relative Costs	
Installation	Low
Life Cycle	Low
Maintenance	Low
Repair	Low
Effective Longevity	Low
Level of Difficulty	
Installation	Low
Repair	Low
Maintenance	Low
Retrofit	Low

Description: Compacted recycled asphalt from asphalt milling operations

Typical Locations:

- Cable barrier
- Edge of pavement
- Guardrail
- Mow edge

Advantages:

- Can be used in most climate conditions
- Applicable for new construction and retrofit
- Low life cycle cost
- Most contractors have equipment to install
- Uses recycled materials from milling operations
- Leave-outs are not required

Limitations and Common Problems:

- Subject to availability
- May become dislodged if not compacted properly
- Subject to loss of compaction over time, allowing weed development

ROCK BLANKET

Relative Costs	
Installation	High
Life Cycle	Low
Maintenance	High
Repair	High
Effective Longevity	High
Level of Difficulty	
Installation	Moderate
Repair	High
Maintenance	Low
Retrofit	High

Description: Rock cobble installed using mortar with or without concrete base

Typical Locations:

- Support posts and poles
- Gore/median
- Slope/embankment

Advantages:

- Aesthetic value determined by color and texture
- Good for use in urban/high-visibility locations
- Applicable for new construction and limited retrofit
- Can be used in most climate conditions
- Low life cycle cost
- Most contractors have equipment to install

Limitations and Common Problems:

- High installation and repair costs if set in mortar
- Can be difficult in retrofit applications due to size of cobble
- Leave-outs may be required due to VMS material rigidity. Refer to AASHTO RDG, MASH, recent research, and/or other guidelines to determine leave-out compliance requirements.

ROCK SLOPE PROTECTION

Relative Costs	
Installation	Low
Life Cycle	Low
Maintenance	Low
Repair	Low
Effective Longevity	Moderate
Level of Difficulty	
Installation	Low
Repair	Low
Maintenance	Low
Retrofit	Low

Description: Rock cobble placed on geosynthetic fabric (herbicide or non-herbicide treated)

Typical Locations:

- Gore/median
- Slope/embankment

Advantages:

- Provides erosion control
- Can be used in most climate conditions
- Low life cycle cost
- Most contractors have equipment to install
- Aesthetic value determined by color and texture
- Applicable for new construction and retrofit

Limitations and Common Problems:

- Limited application areas
- Maximum slope 1V:2H
- Subject to voids filling with windblown soil, allowing weed development
- May require spot herbicide treatments

RUBBER WEED MAT

Relative Costs	
Installation	Moderate/High
Life Cycle	Low
Maintenance	Low
Repair	Low
Effective Longevity	High
Level of Difficulty	
Installation	High
Repair	Moderate
Maintenance	Low
Retrofit	High

Description: Mats consisting of recycled rubber tires adhered together with a resin. Cutouts are often provided for post placement.

Typical Locations:

- Cable barrier
- Support posts and poles
- Guardrail

Advantages:

- No staking/anchoring is required
- Easy to install and replace but is very time consuming, thereby increasing worker exposure
- Different colors available
- Applicable for new construction and retrofit

Limitations and Common Problems:

- Long worker exposure time due to slow installation process
- Potential joint separation if not installed/sealed properly
- Subject to damage from wind, mowers, snow removal equipment; joint separation; and UV degradation

STAMPED ASPHALT PAVEMENT

Relative Installation Cost	
Installation	Moderate/High
Life Cycle	Moderate
Maintenance	High
Repair	High
Effective Longevity	Moderate
Level of Difficulty	
Installation	Moderate/High
Repair	High
Maintenance	Moderate
Retrofit	High

Description: Economical aesthetic treatment for standard asphalt concrete. An imprint tool is used to create pattern(s) while asphalt is still warm and pliable.

Typical Locations:

- Support posts and poles
- Edge of pavement
- Gore/median
- Mow edge

Advantages:

- Installation and repair can be done by standard maintenance equipment
- Aesthetic value determined by colors and patterns
- Faster installation than stamped concrete or pavers, so less worker exposure time to traffic
- Applicable for new construction

Limitations and Common Problems:

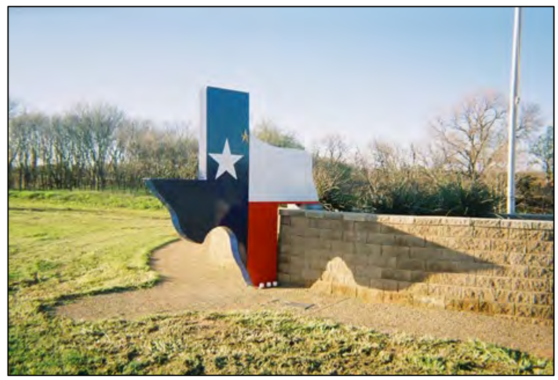
- Use on slopes is difficult for stamping equipment
- Leave-outs may be required due to VMS material rigidity. Refer to AASHTO RDG, MASH, recent research, and/or other guidelines to determine leave-out compliance requirements.
- Difficult to match colors during repair
- UV degradation of color may occur
- Deformation or cracking may occur
- Subject to surface scaring

STANDARD CONCRETE PAVEMENT

Relative Installation Cost	
Installation	High
Life Cycle	Low
Maintenance	Low
Repair	High
Effective Longevity	High
Level of Difficulty	
Installation	Moderate
Repair	High
Maintenance	Moderate
Retrofit	High

Description: Standard concrete mixture

Typical Locations:



- Cable barrier
- Support posts and poles
- Edge of pavement
- Gore/median
- Guardrail
  If using with a strong post guardrail, refer to the STRONG POST GUARDRAIL USE WITH RIGID VMS MATERIALS information sheet for examples of recently tested designs with leave-outs.
- Mow edge
- Slope/embankment

Advantages:

- Aesthetic value determined by color and texture
- Applicable for new construction and limited retrofit
- Can be used in most climate conditions
- Low life cycle cost
- Most contractors have equipment to install

Limitations and Common Problems:

- High installation and repair costs
- Can be difficult in retrofit applications such as existing guardrails due to grading and excavation required for installation
- Leave-outs may be required due to VMS material rigidity. Refer to AASHTO RDG, MASH, recent research, and/or other guidelines to determine leave-out compliance requirements.

WEED CONTROL FIBER MAT

Relative Costs	
Installation	Moderate/High
Life Cycle	Low
Maintenance	Low
Repair	Low
Effective Longevity	High
Level of Difficulty	
Installation	Low
Repair	Low
Maintenance	Low
Retrofit	Moderate

Description: Mats consisting of synthetic polyester fibers made from recycled plastic

Typical Locations:

- Cable barrier
- Support posts and poles
- Guardrail

Advantages:

- Can be used in most climate conditions
- Applicable for new construction and retrofit
- Uses standard installation/maintenance equipment
- Allows for storm water infiltration
- Fire retardant
- Variable width rolls to 6 feet
- Not subject to UV degradation
- Available in various colors for aesthetic appeal
- Applicable for new construction and retrofit

Limitations and Common Problems:

- Areas at ground penetrations should be sealed with caulk or similar material
- Subject to damage from wind, mowers, and snow removal equipment
- Displacement by errant vehicles and maintenance equipment

STRONG POST GUARDRAIL USE WITH RIGID VMS MATERIALS

The VMSs identified and presented do not present specific design guidance for highway safety appurtenances, nor are they a substitute for any other highway design practice. The user should refer to the AASHTO RDG, MASH for successfully tested hardware, and any specific state DOT practices for warrants, proper placement, and maintenance of roadside safety appurtenances when applying these VMSs (AASHTO 2011b, 2016). In addition, before applying any of the techniques described on a proprietary roadside safety hardware device (e.g., guardrail terminal, crash cushion, or breakaway sign support), the manufacturer should be contacted to discuss the potential for the treatment to adversely affect the performance of the manufacturer's safety hardware device.

Mow strips prevent vegetation growth several feet around guardrail installations, including cable barriers, W-beam guardrail, guardrail transitions, and guardrail end treatments. W-beam guardrail posts, guardrail transition posts, and guardrail end treatment posts are treated equally with regard to the application of VMSs. As previously stated, a VMS should not be applied to any proprietary guardrail end treatment without consulting first with the product manufacturer.

Mow strips are typically asphaltic or concrete pavement and vary in thickness from several inches up to 200 mm (8 inches) maximum. Strong post W-beam guardrail posts in mow strips and rock formations face similar problems with regard to facilitating rotation of the strong posts. Details for installation of strong steel post W-beam guardrail posts in mow strips have been developed, which differ from that in rock formations. These details were originally developed and crash tested for use with both steel and wood posts in accordance with NCHRP Report 350 (Ross et al. 1993). More recent research and full-scale MASH testing have been conducted for strong post W-beam guardrail in mow strips with leave-outs, the portion of the mow strip omitted around the base of the post to allow for post rotation. The 31-inch W-beam guardrail system with steel posts in concrete mow strip performed acceptably for both MASH Tests 3-10 and 3-11, and therefore the steel post W-beam system in concrete mow strip is considered acceptable for MASH Test Level Three (TL-3) longitudinal barrier (Sheikh et al. 2019, Moran et al. 2020). In this design, the critical measurement of the leave-out installation is from the back of the post to the edge of the mow strip; this measurement should be a minimum of 175 mm (7 inches). Yet wood post W-beam guardrail testing did not meet MASH TL-3 safety requirements in all cases. Strong post guardrail with 6-inch by 8-inch rectangular wood posts and 7½-inch-diameter round wood posts both failed to meet the MASH TL-3 criteria when installed in mow strips with leave-outs. However, a modified round wood post system with 36-inch embedment (Moran et al. 2020) was full-scale crash tested in a mow strip with leave-outs and did meet MASH TL-3 safety requirements. These recent findings suggest that leave-outs remain a viable method for use in mow strips with steel post W-beam guardrail systems. Wood post W-beam guardrail systems appear to be more sensitive to the use of mow strips and may require further research and/or development of design modifications.

The critical feature of the mow strip installation is the portion of the mow strip around the post omitted for the post rotation, also known as the leave-out. The leave-out's critical measurement is from the back of the post to the edge of the mow strip and should be a minimum of 175 mm (7 inches). For illustrative purposes, Figure 1 shows the detail from the AASHTO RDG (AASHTO 2011b). Leave-outs can be filled with low-strength grout, a two-part polyethylene foam, or other material that has a compressive strength of 0.85 MPa (120 psi) or less. During an impact, the leave-out material allows for some degree of post rotation by deforming or crushing prior to generating sufficient force to cause post failure. Failure of the sacrificial leave-out backfill material also minimizes damage to the surrounding mow strip. Some states backfill with a coarse aggregate material and seal the surface with an asphaltic sealer material. As previously discussed, this is an active area of research and design evolution, and the RDG has not been updated and is out of date for some applications. Always check that a mow strip design has been evaluated in accordance with MASH.

For strong steel post W-beam guardrail posts installed in asphalt or concrete surfacing that is thicker than 200 mm (8 inches), refer to Figure 2 showing AASHTO RDG Figure 5-5l (b) for installation in rock formations (AASHTO 2011b). For these installations, the backfill around the posts is typically a coarse aggregate material. In some locations, it may be beneficial to seal the surface with an asphaltic crack sealant or other similar material to reduce water infiltration

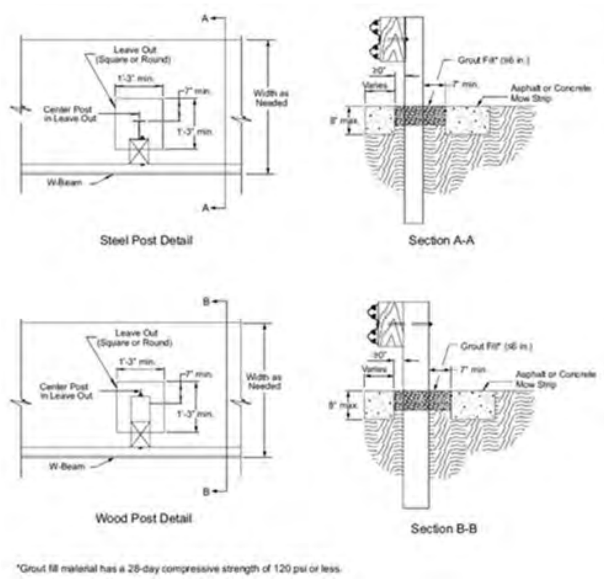


Figure 1. AASHTO RDG Guardrail Post Detail in Mow Strip Application (AASHTO 2011b).

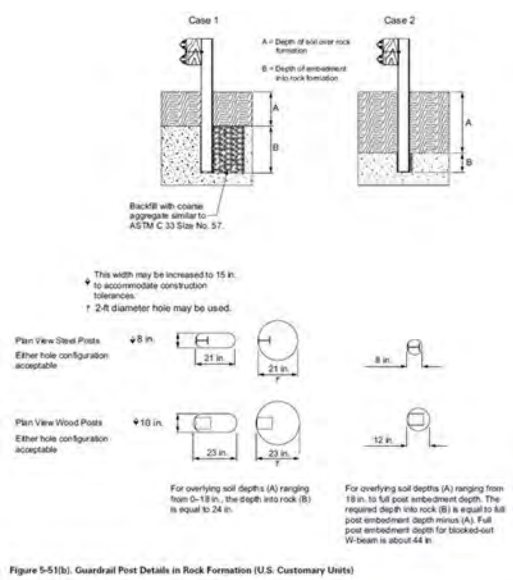


Figure 2. Guardrail Post Details in Rock Formation (AASHTO 2011b).

TxDOT sponsored MASH testing of W-beam guardrail with 36-inch soil embedded, 7½-inch-diameter round wood posts in a concrete mow strip as shown in Figure 3. The tested configuration met the safety performance evaluation guidelines for MASH TL-3 longitudinal barriers. The crash test performed was in accordance with MASH Test 3-11, which involves a 2270P vehicle impacting the TxDOT W-beam guardrail with 7½-inch-diameter round wood posts in a concrete mow strip at a target impact speed and impact angle of 62 mi/h and 25 degrees, respectively.

Figure 3. Round Wood Post in Concrete Mow Strip (Moran et al. 2020).

The 31-inch W-beam guardrail system with steel posts in a concrete mow strip (Figure 4) performed acceptably for both MASH Tests 3-10 and 3-11, and therefore the steel post W-beam system in a concrete mow strip is considered acceptable for MASH TL-3 longitudinal barrier (Moran et al. 2020).

Figure 4. W-beam Guardrail in Concrete Mow Strip (Moran et al. 2020).

Summary

VMSs applied in and around highway safety appurtenances should be done so cognizant of their effect on the performance of everything in the highway design environment. If a VMS is thought to possibly have a performance effect on a highway safety appurtenance, then consideration should be given to crash testing the VMS and safety appurtenance together as a system. As of January 1, 2011, all newly developed hardware must be tested using MASH. Of particular interest to the application of VMSs, the FHWA also issued a memorandum dated January 7, 2016, regarding the federal-aid eligibility of highway safety hardware after December 31, 2016, and the following applies to VMSs (FHWA 2016):

- FHWA will no longer issue eligibility letters for highway safety hardware that has not been successfully crash tested to the 2016 edition of MASH.
- Modifications of eligible highway safety hardware must use criteria in the 2016 edition of MASH for reevaluation and/or retesting.
- Non-significant modifications of eligible hardware that have a positive or inconsequential effect on safety performance may continue to be evaluated using finite element analysis.

For More Information

AASHTO. 2011a. *Guidelines for Vegetation Management*, first edition. Washington, DC.

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APPENDIX D: PENNSYLVANIA DEPARTMENT OF TRANSPORTATION RECYCLING MATERIAL BRIEF: CRUSHED GLASS FACT SHEET

PennDOT RECYCLING MATERIAL BRIEF

Crushed Glass Fact Sheet

Introduction and Background

Pennsylvania industry and consumers generated a considerable volume of waste each year. While some must be disposed in a sanitary landfill or as a hazardous material, other materials can be recovered and recycled. Recycling materials into high value-added products is most desirable if it is economically feasible. Using them in highway construction projects helps dispose of them constructively and avoids filling up landfill space. The possibility of using mixed color crushed glass in roadway construction has shown to be an attractive alternative to aggregate, especially where virgin aggregate sources are scarce and glass cullet is economically priced.

Successful recycling programs have produced large quantities of glass, primarily in the form of bottles and jars. Waste glass constitutes approximately 7 percent of the 200 million tons of municipal solid waste generated annually. A significant amount of glass is recycled directly back to the manufacturer. In the recycling process, some of the glass becomes broken, color-mixed, or otherwise contaminated, and cannot be used in container manufacturing. Crushed glass also known as glass cullet refers to waste glass produced as a result of breakage and rejection on quality control grounds during the manufacturing process. Some of this glass cullet is again used by manufacturer for the production of new glass containers, but it does have limitations such as color sorting and transportation.

PennDOT in conjunction with the Pennsylvania Department of Environmental Protection completed a research program at Drexel University (Drexel) to determine several of the basic physical, mechanical, and hydraulic properties of two sources of glass cullet in Southeastern Pennsylvania. D.M. Stoltzfus & Son, Inc. (Talmage, PA) and Todd Heller, Inc. (Northampton, PA) provided the glass cullet for this program. The physical property tests were performed in its fully processed (crushed or sieved), or its as-received (AR) condition. Tests were also conducted on the coarse fraction (CF) of each cullet sample which was selected to be representative of minimally processed glass cullet. A copy of the laboratory research report can be obtained upon request from the Bureau of Design, Environmental Quality Assurance Division, Pollution Prevention Section at 717-787-1024.

This fact sheet provides information on glass cullet physical properties, engineering parameters, and applications for the PennDOT use in civil engineering applications. This fact sheet is divided into the following sections:

Material Properties - describes the physical properties and engineering parameters of glass cullet.
Applications - describes glass cullet applications.
Specifications - presents existing PennDOT specifications.
Conclusions - presents conclusions and discusses implementation issues.

Material Properties

General Observations

Well processed and screened glass cullet typically does not contain debris (deleterious materials) in sufficient quantities to affect the engineering properties of the glass cullet (when within the less than 2% by weight). The debris consisted primarily of bottle labels, and metal and plastic caps. The supplied materials were angular; however, the particles were sufficiently small so as to not pose a handling hazard to the laboratory personnel, who were able to safely handle the glass using their bare hands.

Engineering Parameters

The test results are summarized below followed by a description of the physical properties, and engineering parameters evaluated and a comparison to traditional aggregate material properties:

Summary of Engineering Parameters of Glass Cullet

Test	Parameter	Results[1] AR	Results[1] CF
Water Content ASTM D2216	w_n (%)	2.4-4.2	---
Debris Content Gravimetric	w_{debris} (%)	0.3-1.8	---
Specific Gravity ASTM D854	G_S (-)	2.48-2.49	---
Los Angeles Abrasion ASTM C131	wear (%)	24-25	---
Standard Compaction ASTM D698	$\gamma_{d,\,max}$ (kN/m^3) $\gamma_{d,\,max}$ (lb/ft^3) w_{opt} (%)	107.5-111.9 16.9-17.6 11.9-13.2	93.5-99.2 14.7-15.6 6.5-12
Modified Compaction ASTM D1557	$\gamma_{d,\,max}$ (kN/m^3) $\gamma_{d,\,max}$ (lb/ft^3) w_{opt} (%)	111.9-117 17.6-18.4 10.8	108.1 17.0-17.1 7.8-9.9
Hydraulic Conductivity* ASTM D3080	k (cm/s)	1.61-6.45 x 10^{-4}	4.91 x 10^{-3} - 7.22 x 10^{-4}
Direct Shear Test* ASTM D3080	ϕ_{ds} (°)	56-61	48-54
CD** Triaxial Test* US Army COE	ϕ_{tx} (°)	46-47	44-45

*Completed at 90% min. modified proctor density; ** Consolidated-drained
[1] Values based on two sources.

- Water Content (ASTM D-2216) - Six water content tests were performed on the glass cullet in its AR condition. The results indicate that there was relatively little variation in water content for each supplier. This is to be expected from capillary effects (i.e., finer materials retain more water).
- Debris Content - Gravimetric debris content tests were performed on the glass cullet in its as- received condition. For each supplier, a bulk sample was collected from a drum container and weighed. Debris (material other than glass, e.g., bottle caps and labels, plastic tops, etc.) was manually removed and the sample was reweighed. The debris content was computed as the weight of debris divided by the weight of glass cullet. These materials had gravimetric debris contents of 0.3% and 1.8%.
- Specific gravity (ASTM D-854) is a measure of a material's density, affects the dry, partially saturated, and saturated unit weights of porous media. Specific gravity values for crushed natural aggregate range from 2.60 to 2.83. Based on PennDOT's test results, the specific gravities for fine glass cullet range from 2.48 to 2.49. The values are about 5% to 10% lower than those of most natural aggregates.
- Gradation (ASTM D-653) is defined as (grain-size distribution) proportions by mass of a soil or fragmented rock distributed in specified particle-size ranges. It can affect engineering properties such as compaction, permeability, filtration, and shear strength. Gradation is obtained by sieve analysis. PennDOT found that the gradation of glass cullet is generally similar to crushed rock and gravely sand and is controlled by the cullet processing method. Specifications will dictate the gradation required for each application.
- Los Angeles Abrasion Test (ASTM C-131) assesses the durability and abrasion resistance of aggregates. Durability is a material classification property that affects its suitability for roadway base

course and fills under fluctuating loads. A Los Angeles Abrasion Test was performed by PennDOT on samples of glass cullet in their AR condition and had values of 24% and 25%. Natural aggregates typically have wear values in the range of 10% to 35%

- Direct Shear Tests (ASTM D-3080) is the maximum resistance on a soil or rock to shearing stresses. Shear strength is a design consideration that affects bearing capacity and is expressed by the angle of internal friction measured in degrees. Typical granular soils have a friction angle ranging from 27 (loose, silty sand) degrees to 55 degrees (dense, medium size gravel). Shear strength is a major design consideration for construction with glass cullet in embankments, roadway base courses, and engineering fill under foundations. PennDOT's test results indicate that the strength of cullet is about the same as natural aggregate. However, the shear strength tests results suggested that when compacted, crushed glass exhibited relatively little cohesion. This may reflect the natural variability of the crushed glass, its grain-size distribution, compacted density, or moisture content.

- Compaction (ASTM D 653) is the densification of a soil by means of mechanical manipulation. Compaction is a design consideration that affects density control. Compaction characteristics include relationship of density and moisture content, effect of compaction method on density and potential gradation change, and sensitivity of material to weather conditions. Cullet and cullet-aggregate mixtures have favorable compaction characteristics. Similar to many natural aggregates, PennDOT's Standard and Modified Proctor compaction tests exhibit maximum dry densities that exceeded those of the Standard Proctor values by approximately 5% to 10%. The moisture-density curves results exhibited the characteristic convex shape of natural aggregates, suggesting that the glass cullet behaves in a manner similar to natural aggregates. However, heavy field compaction equipment can significantly affect density values for 100 percent cullet fills because of the gradation changes. *In addition, PennDOTs test results also found that the compacted density of cullet is not sensitive to the moisture content, which means that cullet material can be placed and compacted during wet weather.*

- Permeability (ASTM D 653) is a design consideration in civil drainage applications such as foundations drainage, drainage blankets, and French drains, and in leachate collection and gas venting layers. Typical granular soils (sand or sand-gravel mixtures) have permeabilities ranging from 0.01 to 0.001 cm/sec. Data found from PennDOT research found that permeability tests of 100 percent glass cullet have permeabilities ranging from 0.04 to 0.06 cm/sec for fine cullet and 0.18 to 0.26 cm/sec for coarse cullet. This is comparable to natural sand and gravel. Therefore, drainage applications can use 100 percent glass cullet for fill material.

Applications

Glass cullet is typically evaluated as classified well graded sand by the Unified Soil Classification System, or as a Number 10 aggregate by the AASHTO. Potential aggregate applications for glass cullet and cullet-aggregate mixtures are categorized below:

General Construction Backfill	Drainage
Stationary loads (fill beneath foundations)	Retaining Wall Backfill
Landscaping fill	Foundation Drainage
Roadway Construction	Septage Field Media
Base course	Sand Filters (Wastewater)
Subbase or subgrade layer	Drainage Blanket
Embankment	French Drains
Utility Construction	Landfill Construction
Pipe Bedding	Leachate collection layer system
Trench Backfill	

Other uses may exist, but the incorporation of glass in hot-mix asphalt and structural concrete (other than flowable fill) may lead to performance problems.

Specifications

Recycled glass aggregate has been used in PennDOT projects for pipe bedding and trench backfill in place of virgin rock aggregate. These applications have resulted in cost-savings, but are still considered trial uses, since the availability and quality of recycled glass aggregate is highly variable. These glass cullet specifications provided below are available on PennDOT's Engineering and Construction Management Website.

- Embankment fill – P – B02061
- Embankment fill – Section 206.2(a)1.1b,e, or 206.2(a)2
- Flowable fill – Section 220.2(j)

Conclusions

The utilization of glass cullet in civil engineering applications is a potentially emerging market, subject to variability in costs of materials and contractors' perceptions of risk associated with glass cullet construction. However, the viable applications for glass cullet utilization offer many benefits including: creation of a product market for mixed glass; diversion of recyclable glass from disposal in a landfill; reduction in need for natural mineral resources; and improving the performance of poor-quality gravel in cullet-aggregate mixtures.

Glass cullet and cullet-aggregate blends have been used in numerous civil engineering applications as an alternative to conventional granular materials. Glass cullet has physical properties similar to granular materials. The computational methods and tests to demonstrate glass cullet performance essentially are the same methods and tests used for granular materials. Several specifications can be applied to the usage of glass cullet in unbound construction aggregate applications. Cullet content is dependent upon the application, availability, and specification.

APPENDIX E: ROADSIDE SAFETY OVERVIEW

A HISTORY OF ROADSIDE SAFETY

Highway design was reaching maturity during the 1940s, and focus shifted to safety in the late 1960s. In 1956, President Dwight Eisenhower signed the Federal-Aid Highway Act of 1956. The bill created a 41,000-mile “National System of Interstate and Defense Highways.” The interstates were to provide a uniform transcontinental roadway design network that would eliminate unsafe roads, inefficient routes, and traffic jams and provide fast safe transcontinental travel. The 1960s focused on safety for both automobiles and highways because many motorists were losing their lives in automobile accidents. The National Traffic and Motor Vehicle Safety Act in 1966 empowered the federal government to set and administer new safety standards for motor vehicles and road traffic safety. The act was the first mandatory federal safety standards for motor vehicles. During the 1960s, highway engineers also began to focus on the design of the roadside as well as the roadway itself. The forgiving roadside concept recognized that motorists do run off the roadway and that serious accidents and injuries could be lessened if a roadside had a clear and traversable recovery area. Collisions with fixed objects have been significantly reduced thanks to federal and state transportation officials’ dedication to the forgiving roadside concept.

This roadside recovery area came to be known as the *clear zone* and starts at the edge of the traveled way and extends out to a current unshielded minimum of 3 m (10 feet) for low-speed rural collectors and local roads. The desired clear zone width is a function of traffic volumes, speeds, and roadside geometry. Ideally, the clear zone should be free of obstacles such as unyielding sign and luminaire supports, non-traversable drainage structures, utility poles, steep slopes, and other fixed objects. The AASHTO RDG generally defines fixed objects as the following:

- Post/pole
- Culvert/ditch
- Guardrail, crash cushion, or traffic barrier
- Tree
- Curb
- Embankment
- Fence
- Other fixed object (bridge, wall, bush, etc.)

AASHTO has design options for the treatment of undesirable roadside objects, and those options are generally considered in the following order:

- Remove the obstacle or redesign it so it can be safely traversed.
- Relocate the obstacle to a point where it is less likely to be struck.
- Reduce impact severity by using an appropriate breakaway device.
- Redirect a vehicle by shielding the obstacle with a longitudinal traffic barrier and/or crash cushion.
- Delineate the obstacle if the above alternatives are not appropriate

As transportation facilities continue to expand and most often without the benefit of additional ROW, the most common practice is to shield the obstacle with some type of roadside barrier or attenuator. However, this practice, because of limited ROW, in essence comprises the concept of the clear recovery zone. The placement of re-directive roadside barriers, as an example, that are intended to protect the motorist from an immovable hazard(s) has now created a secondary hazard to the motorists and has increased the exposure area. However, these barriers are installed where the consequence of striking the barrier is still less than the consequence of striking the object(s) the barrier is protecting the vehicle from striking. Many objects are placed along the roadside and within the clear zone or roadway environment, such as sign supports, that provide information that guides, warns, and regulates the motorist's operation along the highway. Likewise, barriers are used to shield steep roadside slopes and protect infrastructure, trees, and other hazards. All these types of devices placed in roadway environment must be subjected to full-scale vehicular crash testing to verify that they are indeed crashworthy.

The procedures for crash testing and evaluating highway safety appurtenances have evolved from the first published guidelines in 1962, *Highway Research Correlation Services Circular 482,* to the current 2006 MASH. For approximately six decades, the United States has been committed to highway safety. Guidelines for crash testing roadside safety appurtenances originated in 1962 with a one-page document—Highway Research Circular 482, entitled *Proposed Full-Scale Testing Procedures for Guardrails.* This document includes four specifications on test article installation, one test vehicle, six test conditions, and three evaluation criteria. Since the release of Highway Research Circular 482, six more documents have followed pertaining to crash testing and evaluating highway safety appurtenances. Those documents are NCHRP Reports 115, 118, 153, 230, and 350 and Transportation Research Circular 191. A brief discussion of each document follows.

In 1971, *NCHRP Report 115: Guardrail Performance Design* and *NCHRP Report 118: Location, Selection, and Maintenance of Highway Traffic Barriers* were published. NCHRP Report 115 examines and uses a six degrees of freedom mathematical model to describe the dynamic behavior of vehicle impacts into barriers. The study was one of the first of its kind to examine the correlation between computer-predicted behavior (simulation) of vehicle/barrier impacts and full-scale crash testing. In addition, human impact tolerance levels were examined and evaluated for 25 full-scale crash tests. It was first suggested here that occupants would require lap and shoulder belts to avoid serious injury when impacting roadside barriers. NCHRP Report 118 presents a synthesis of existing information on warrants, service requirements, and performance criteria for all traffic barrier systems. Vehicle impact characteristics and dynamic performance and evaluation criteria are presented for all types of highway safety barrier hardware.

In 1974, *NCHRP Report 153: Recommended Procedures for Vehicle Crash Testing of Highway Appurtenances* was published. This 16-page document provides the first complete test matrix for evaluating safety features. Data collection methods, evaluation criteria, and limited guidance on reporting formats are included. These procedures gained wide acceptance following their publication, but it was recognized at that time that periodic updating would be needed.

Published in 1978, *Transportation Research Circular 191: Recommended Procedures for Vehicle Crash Testing of Highway Appurtenances* provides limited interim changes to NCHRP

Report 153 to address minor changes requiring modified treatment of problem areas. Extensive revision and update to these procedures were made in 1981 with the publication of the 42-page *NCHRP Report 230: Recommended Procedures for the Safety Performance Evaluation of Highway Appurtenances.*

In 1993, *NCHRP Report 350: Recommended Procedures for the Safety Performance Evaluation of Highway Features* was published. This 132-page document represents a comprehensive update to crash test and evaluation procedures. It incorporates significant changes and additions to procedures for safety performance evaluation, and updates reflecting the changing character of the highway network and the vehicles using it. NCHRP Report 350 contains guidelines for evaluating the safety performance of roadside features, such as longitudinal barriers, terminals, crash cushions, and breakaway structures. FHWA formally adopted this document as the national standard in 1993 with an implementation date of late 1998. In 1998, AASHTO and FHWA agreed that most types of safety features installed along the National Highway System must meet NCHRP Report 350 safety performance evaluation criteria. FHWA formally adopted the new performance evaluation guidelines for highway safety features set forth in NCHRP Report 350 as a “Guide or Reference” document in the *Federal Register*, Volume 58, Number 135, dated July 16, 1993, which added paragraph (a)(13) to 23 CFR, Part 625.5. FHWA subsequently mandated that starting in September 1998, only highway safety appurtenances that have successfully met the performance evaluation guidelines set forth in NCHRP Report 350 may be used on new construction projects on the National Highway System. Since the report’s adoption, many states, counties, and municipalities have begun to use crashworthy safety appurtenances.

NCHRP Report 350 was unique in that it created six test levels. Test levels one through three (TL-1 through TL-3) were based on speed: TL-1 was 50 km/h (30 mi/h), TL-2 was 70 km/h (43 mi/h), and TL-3 was 100 km/h (62 mi/h). Three additional test levels (TL-4 through TL-6) were for heavier commercial-type vehicles at 80 km/h (50 mi/h). The test vehicle weights ranged from 820 kg (1800 lb) to 36,000 kg (80,000 lb).

Through various pooled-fund studies and other research projects, FHWA and state DOTs tested the most widely used nonproprietary safety appurtenances. Additionally, manufacturers worked toward recertification of their proprietary products. Ultimately, numerous changes and modifications to existing hardware were required to comply with NCHRP Report 350. Many of these changes were attributed to the change from the 4500-lb passenger vehicle to the 4400-lb (2000P) pickup truck. The pickup truck represented an SUV class of vehicle that had a higher CG and was inherently less stable than the large passenger vehicle used under NCHRP Report 230. In addition, the pickup truck had a shorter front overhang, often resulting in snagging of the front wheel and subsequent displacement of the wheel and tire into the floor/toe pan. As a result of snagging and wheel displacement, excessive intrusion into the occupant compartment was frequently observed. Work zone devices, such as portable sign stands and barricades, were tested, many for the first time. These devices often failed due to intrusion into the small 1800-lb (820C) passenger compartment through the roof and windshield.

In 2009, AASHTO published MASH, the update to NCHRP Report 350. MASH provides:

- A basis on which researchers and user agencies can compare the impact performance merits of candidate safety features

- Guidance for developers of new safety features
- A basis on which user agencies can formulate performance specifications for safety features

MASH reflected a changing vehicle fleet in that the small car weight increased to 1100 kg (2420 lb), the pickup truck weight increased to 2270 kg (5000 lb), and the TL-4 single-unit truck weight increased from 8000 kg (17,600 lb) to 10,000 kg (22,040 lb). In addition, the impact angle for the small car increased from 20 degrees to 25 degrees. The impact angles for terminals and crash cushions also increased to 25 degrees. An extensive cable barrier test matrix was presented for both level terrain and in ditches. Much like in NCHRP Report 350, an implementation plan also existed in MASH. An example of a typical test matrix in MASH is Table 2-2A, "Recommended Test Matrices for Longitudinal Barriers," and is presented in Figure E1. This table illustrates the test levels, speed, angle, impact severity, and evaluation criteria used for evaluating a longitudinal barrier. The normal or standard test level for most highway applications is TL-3—100 km/h (62 mi/h). Research (Mak et al. 1986) (NCHRP in-progress) and reconstructions of run-off-the-road passenger vehicle crashes on high-speed roadways indicate that an impact speed of 100 km/h (62 mi/h) and an impact angle of 25 degrees approximate the 85th percentile of the real-world impacts. These conditions are reflected in MASH TL-3.

TABLE 2-2A. Recommended Test Matrices for Longitudinal Barriers

Test Level	Barrier Section[c]	Test No.	Vehic.	Impact Speed,[a] mph (km/h)	Impact Angle,[a] θ, deg.	Impact Point	Acceptable IS Range,[a] kip-ft (kJ)	Evaluation Criteria[b]
1	Length-of-Need	1-10	1100C	31 (50.0)	25	(c)	≥13 (17.4)	A,D,F,H,I
		1-11	2270P	31 (50.0)	25	(c)	≥27 (36.0)	A,D,F,H,I
	Transition	1-20[d]	1100C	31 (50.0)	25	(c)	≥13 (17.4)	A,D,F,H,I
		1-21	2270P	31 (50.0)	25	(c)	≥27 (36.0)	A,D,F,H,I
2	Length-of-Need	2-10	1100C	44 (70.0)	25	(c)	≥25 (34.2)	A,D,F,H,I
		2-11	2270P	44 (70.0)	25	(c)	≥52 (70.5)	A,D,F,H,I
	Transition	2-20[d]	1100C	44 (70.0)	25	(c)	≥25 (34.2)	A,D,F,H,I
		2-21	2270P	44 (70.0)	25	(c)	≥52 (70.5)	A,D,F,H,I
3	Length-of-Need	3-10	1100C	62 (100.0)	25	(c)	≥51 (69.7)	A,D,F,H,I
		3-11	2270P	62 (100.0)	25	(c)	≥106 (144)	A,D,F,H,I
	Transition	3-20[d]	1100C	62 (100.0)	25	(c)	≥51 (69.7)	A,D,F,H,I
		3-21	2270P	62 (100.0)	25	(c)	≥106 (144)	A,D,F,H,I
4	Length-of-Need	4-10	1100C	62 (100.0)	25	(c)	≥51 (69.7)	A,D,F,H,I
		4-11	2270P	62 (100.0)	25	(c)	≥106 (144)	A,D,F,H,I
		4-12	10000S	56 (90.0)	15	(c)	≥142 (193)	A,D,G
	Transition	4-20[d]	1100C	62 (100.0)	25	(c)	≥51 (69.7)	A,D,F,H,I
		4-21	2270P	62 (100.0)	25	(c)	≥106 (144)	A,D,F,H,I
		4-22	10000S	56 (90.0)	15	(c)	≥142 (193)	A,D,G
5	Length-of-Need	5-10	1100C	62 (100.0)	25	(c)	≥51 (69.7)	A,D,F,H,I
		5-11	2270P	62 (100.0)	25	(c)	≥106 (144)	A,D,F,H,I
		5-12	36000V	50 (80.0)	15	(c)	≥404 (548)	A,D,G
	Transition	5-20[d]	1100C	62 (100.0)	25	(c)	≥51 (69.7)	A,D,F,H,I
		5-21	2270P	62 (100.0)	25	(c)	≥106 (144)	A,D,F,H,I
		5-22	36000V	50 (80.0)	15	(c)	≥404 (548)	A,D,G
6	Length-of-Need	6-10	1100C	62 (100.0)	25	(c)	≥51 (69.7)	A,D,F,H,I
		6-11	2270P	62 (100.0)	25	(c)	≥106 (144)	A,D,F,H,I
		6-12	36000T	50 (80.0)	15	(c)	≥404 (548)	A,D,G
	Transition	6-20[d]	1100C	62 (100.0)	25	(c)	≥51 (69.7)	A,D,F,H,I
		6-21	2270P	62 (100.0)	25	(c)	≥106 (144)	A,D,F,H,I
		6-22	36000T	50 (80.0)	15	(c)	≥404 (548)	A,D,G

a See Section 2.1.2 for tolerances on impact conditions.
b See Table 5-1.
c See Figure 2-1 and Section 2.3.2 for impact point.
d Test is optional.

Figure E1. Recommended Test Matrices for Longitudinal Barriers (AASHTO 2016).

On November 12, 2015, FHWA issued a memorandum indicating that all modifications to NCHRP 350–tested devices will require testing under MASH to receive a federal-aid eligibility letter from FHWA. In addition, a *Federal Register* notice was also issued regarding this action. This action provided a significant step forward to the implementation of MASH. Furthermore, another FHWA-issued memorandum dated January 7, 2016, regarding the federal-aid eligibility of highway safety hardware after December 31, 2016, says that:

- FHWA will no longer issue eligibility letters for highway safety hardware that has not been successfully crash tested to the 2016 edition of MASH.
- Modifications of eligible highway safety hardware must use criteria in the 2016 edition of MASH for reevaluation and/or retesting.

- Non-significant modifications of eligible hardware that have a positive or inconsequential effect on safety performance may continue to be evaluated using finite element analysis.

Highway safety appurtenances will continue to evolve, and guidance will be updated to reflect changes in the vehicle population and new knowledge about vehicle/safety hardware and vehicle/occupant interactions.

HIGHWAY SAFETY APPURTENANCE PERFORMANCE EVALUATION

The goal of a highway safety appurtenance/feature, as previously discussed, is to provide a forgiving roadway environment so that when an errant motorist leaves the roadway, the risk of a serious crash is reduced. The goal is to reduce the risk of serious injury or death. When the roadside cannot be made clear of all fixed objects or obstructions and/or cannot be made to be traversable, then a safety appurtenance is used so that the consequences of striking the device are less severe than the fixed object or terrain feature it is protecting. The safety appurtenance used should be crashworthy and evaluated in accordance with the appropriate guidelines at the time the device is installed, such as is currently used (AASHTO 2016).

A highway safety appurtenance is evaluated based on the performance of full-scale crash tests, as previously discussed. A full-scale crash test is defined by the impact speed and angle, the weight of the impacting vehicle, and the impact location. These parameters are selected to represent the "worst practical condition" and are believed to represent the 85th percentile crash severity. The safety performance of a highway appurtenance cannot be measured directly. However, the crashworthiness performance of an appurtenance can be evaluated in terms of the risk of injury to occupants of the impacting vehicle, the structural adequacy of the safety feature, the exposure to workers and pedestrians that may be behind a barrier or in the path of debris resulting from impact with a safety feature, and the post-impact behavior of the vehicle. This philosophy has been stated in NCHRP Report 230 and reiterated in both NCHRP Report 350 and AASHTO MASH.

As previously stated, the crashworthy performance of a highway safety appurtenance is evaluated in terms of structural adequacy, occupant risk, and post-impact vehicle trajectory. A brief discussion of each of these evaluation criteria is presented hereafter. AASHTO MASH provides a thorough discussion of how the crash performance of a highway safety appurtenance is evaluated through crash testing. The criteria for evaluating structural adequacy in MASH are shown in Figure E1, which reproduces MASH Table 5-1A. As noted in MASH, the structural adequacy criteria refer to the structural requirements associated with the impact itself and no other structural aspects of the device. For example, the criteria do not imply that a sign support system that meets the structural adequacy requirements of a test will meet the structural adequacy requirements of wind and ice loads or other environmental considerations when applicable.

Table E1. Safety Evaluation Guidelines for Structural Adequacy.

Evaluation Factors	Evaluation Criteria	Applicable Tests
Structural Adequacy (see Section 5.2.1)	A. Test article should contain and redirect the vehicle or bring the vehicle to a controlled stop; the vehicle should not penetrate, underride, or override the installation although controlled lateral deflection of the test article is acceptable.	10, 11, 12, 20, 21, 22, 30a, 31a, 32a, 33a, 34a, 35, 36, 37a, 38a
	B. The test article should readily activate in a predictable manner by breaking away, fracturing, or yielding.	60, 61, 62, 70, 71, 72, 80, 81, 82
	C. Acceptable test article performance may be by redirection, controlled penetration, or controlled stopping of the vehicle.	30b, 31b, 32b, 33b, 34b, 37b, 38b, 40, 41, 42, 43, 44, 50, 51, 52, 53, 90, 91

a = non-gating terminals and crash cushions, b = gating terminals and crash cushions

Occupant risk is evaluated according to measured vehicular accelerations that occur as a function of the highway safety appurtenance performance and its effect on the external structural design of the test vehicle. Whereas the highway engineer is ultimately concerned with the safety of the vehicle's occupants, the occupant risk criteria of MASH Table 5-IB, shown as Table E2, are considered as guidelines for generally acceptable dynamic performance.

Table E2. Safety Evaluation Guidelines for Occupant Risk.

Evaluation Factors	Evaluation Criteria			Applicable Tests
Occupant Risk (see Section 5.2.2)	D. Detached elements, fragments, or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present undue hazard to other traffic, pedestrians, or personnel in a work zone. Deformations of, or intrusions into, the occupant compartment should not exceed limits set forth in Section 5.2.2 and Appendix E.			All
	E. Detached elements, fragments, or other debris from the test article, or vehicular damage should not block the driver's vision or otherwise cause the driver to lose control of the vehicle.			70, 71, 72
	F. The vehicle should remain upright during and after collision. The maximum roll and pitch angles are not to exceed 75 degrees.			All except those listed in Criterion G
	G. It is preferable, although not essential, that the vehicle remain upright during and after collision.			12, 22
	H. Occupant impact velocities (see Appendix A, Section A5.2.2 for calculation procedure) should satisfy the following limits:			
	Occupant Impact Velocity Limits, ft/s (m/s)			
	Component	Preferred	Maximum	
	Longitudinal and Lateral	30 ft/s (9.1 m/s)	40 ft/s (12.2 m/s)	10, 11, 20, 21, 30, 31, 32, 33, 34, 35, 36, 37, 38, 40, 41, 42, 43, 44, 50, 51, 52, 53, 80, 81, 82, 90, 91
	Longitudinal	10 ft/s (3.0 m/s)	16 ft/s (4.9 m/s)	60, 61, 62, 70, 71, 72
	I. The occupant ridedown acceleration (see Appendix A, Section A5.2.2 for calculation procedure) should satisfy the following limits:			
	Occupant Ridedown Acceleration Limits (G)			
	Component	Preferred	Maximum	
	Longitudinal and Lateral	15.0 G	20.49 G	10, 11, 20, 21, 30, 31, 32, 33, 34, 35, 36, 37, 38, 40, 41, 42, 43, 45, 50, 51, 52, 53, 54, 60, 61, 62, 70, 71, 72, 80, 81, 90, 91

Post-impact vehicular response is a measure of the potential of the vehicle to result in a secondary collision with other vehicles and/or fixed objects, thereby increasing the risk of injury to the occupants of the impacting vehicle and/or other vehicles. Table E3, which reproduces MASH Table 5-1C, provides the guidelines for post-impact vehicular response.

Table E3. Safety Evaluation Guidelines for Post-Impact Vehicular Response.

Evaluation Factors	Evaluation Criteria	Applicable Tests
Post-Impact Vehicular Response (see Section 5.2.3)	J. through M. Reserved.	
	N. Vehicle trajectory behind the test article is acceptable.	30b, 31b, 32b, 33b, 34b, 37b, 38b, 40, 41, 42, 43, 44, 45, 60, 61, 70, 71, 72, 80, 81, 82, 90, 91

A = non-gating terminals and crash cushions, b = gating terminals and crash cushions

AASHTO MASH says that in addition to satisfying these impact performance evaluation criteria in a series of crash tests, the user agency should continue to monitor a safety device's field performance through in-service performance evaluations because its performance cannot necessarily be measured by a series of a few tests alone. Crash tests are performed in a controlled environment, and while a safety appurtenance may meet all test and evaluation criteria, the device may encounter field or in-service conditions that may not have been evaluated in testing.

The discussion hereafter presents material to aid the designer in applying the understanding and the application of how a safety appurtenance is evaluated with regard to structural adequacy, occupant risk, and vehicle trajectory. Examples are presented, as an introduction, to assist in guiding the designer through the thought process of the selection, design, and crash performance of a terminal and sign support.

An end terminal for a concrete safety shape roadside barrier/guardrail and a sign support are unique and in some respects unlike most traditional engineering design. In traditional engineering design, a product is designed and built to sustain or exceed a specific load or structural requirement. In highway safety appurtenance engineering, a design window methodology is used. An end terminal, for example, is designed to withstand the impact of a vehicle and bring that vehicle to a controlled stop at minimal deceleration levels and/or safely redirect the vehicle to the roadway without placing other motorists on the road at risk. Thus begins the dilemma: the highway structure must be structurally adequate to redirect an errant vehicle when struck along its side while yielding or forgiving enough to provide acceptable occupant acceleration ridedown levels when struck on or near its end or terminus, in accordance with values presented in MASH Table 5-1B.

Unlike conventional structural design, forgiving devices must not be overdesigned. The upper bound for strength may be more critical than the lower bound. In lay terms, this means that the strength must be just strong enough but not overly strong. The goal of designing any roadside safety appurtenance is to reduce risk to the errant motorist to the lowest level practical. For a longitudinal barrier end terminal, structural adequacy simply means that the terminal must stop the vehicle in a controlled manner or in some cases prevent the device from gating and allowing the vehicle to penetrate or pass to the other side of the installation. If the vehicle is not brought to a controlled stop, then it may require redirecting the vehicle along the barrier's travel side longitudinal axis. In other words, the vehicle cannot be permitted to reach through or over the barrier and reach what the barrier is protecting.

Controlled stop, as noted previously, refers to safely decelerating an errant vehicle without causing undue harm to its occupants. The external forces exerted on the errant vehicle from the terminal are or may be the result of metal or other materials. The terminal is constructed of deforming the support posts, if applicable, anchored into or onto the ground or road surface, deforming and displacing through the soil or detachment from their method of anchoring to the road surface or base. The energy-absorbing elements of a terminal should not be altered in any way from its design because this will likely alter its crashworthy performance. The energy-absorbing elements can literally be any part of the terminal's design. The performance of a guardrail, guardrail terminal, and guardrail transition is typically very dependent on the displacement of the supporting posts displacing through the soil in a controlled manner. Anything done to alter the characteristics of the way the posts displace through the soil can seriously alter the performance of the safety appurtenance.

The absorption of kinetic energy by displacing the posts through the soil is part of the energy-absorbing ability of the guardrail system and should not be altered. A change in energy-absorbing contribution from one system component such as a post, whether it be more or less energy contribution, can affect how the other system component functions. In the example of guardrail, if a post is restrained from rotating properly, it can cause additional energy transfer to the metal beam element of the guardrail and thus result in possibly tearing or rupturing of the rail. This phenomenon can be readily observed if an improperly constructed concrete or asphalt mow strip is added around wood guardrail posts. The restrained posts do not rotate and consume energy, the posts fracture, excessive deflection of the guardrail occurs, excessive energy is transferred to the rail, and this rail ruptures, allowing the impacting vehicle to penetrate the rail. This phenomenon can also be true of surface-mounted posts if the designed post failure mechanism is altered. Additionally, the vehicle and components of the vehicle, such as the tire and suspension, can snag on the post(s) and/or form a pocket in the rail. This leads to snagging and results in rupturing the rail and frequently excessive deformations of the occupant compartment, which may also lead to excessive changes in occupant velocities and ridedown accelerations.

For the example of a sign support, the sign support must be designed structurally to support the dead load of the sign panel and be capable of sustaining the wind and ice loads the support(s) and sign panel will be subjected to while also being capable of safely yielding to an impacting vehicle in a controlled manner. In this example, *controlled manner* refers to:

- When the sign is struck, it must break away or yield to the impacting vehicle while not causing excessive change in occupant impact velocity or excessive occupant ridedown accelerations
- The trajectory or rotation of the detached sign installation (i.e., sign support, sign panel, and their associated components) over the vehicle should not penetrate into the occupant compartment or cause excessive deformation to the windshield or roof.

The occupant risk evaluation criteria of these values are presented in MASH Table 5-1B, as previously presented, for sign support Tests 60, 61, and 62 for this example. In addition, a detailed discussion of assessing structural adequacy, occupant risk, and deformation and post-impact vehicular response is given in MASH Sections 5.2.1 through 5.2.3, respectively. A discussion of the supporting research of the same is presented in MASH Appendices A5.2.1 through A5.2.3. Anything done to change the way the support is anchored into or onto the ground can greatly affect the sign installation's ability to yield and can cause excessive occupant risk values including excessive deformation and intrusion into the vehicle occupant compartment.

This appendix provides a general discussion of the performance of two types of highway safety appurtenances. The key themes are:

- Designers seek to provide a forgiving roadway environment.
- Highway safety appurtenances should be crash tested and evaluated in accordance with FHWA/AASHTO crash testing guidance (currently MASH).
- All crash-tested appurtenances are evaluated with regard to their structural adequacy, occupant risk, and post-impact trajectory performance.