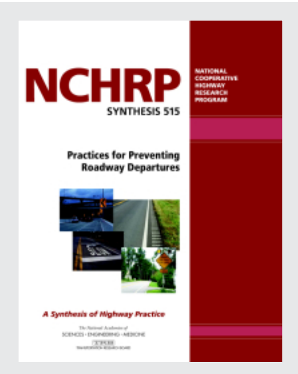

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP SYNTHESIS 515

Practices for Preventing Roadway Departures

A Synthesis of Highway Practice

Hugh W. McGee, Sr.
Annandale, VA

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2018

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research is the most effective way to solve many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments 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, United States Department of Transportation.

The Transportation Research Board (TRB) of the National Academies of Sciences, Engineering, and Medicine was requested by AASHTO to administer the research program because of TRB's recognized objectivity and understanding of modern research practices. TRB is uniquely suited for this purpose for many reasons: TRB maintains an extensive committee structure from which authorities on any highway transportation subject may be drawn; TRB possesses avenues of communications and cooperation with federal, state, and local governmental agencies, universities, and industry; TRB's relationship to the National Academies is an insurance of objectivity; and TRB maintains a full-time staff of specialists in highway transportation matters to bring the findings of research directly to those in a position to use them.

The program is developed on the basis of research needs identified by chief administrators and other staff of the highway and transportation departments, by committees of AASHTO, and by the Federal Highway Administration. Topics of the highest merit are selected by the AASHTO Special Committee on Research and Innovation (R&I), and each year R&I's recommendations are proposed to the AASHTO Board of Directors and the National Academies. Research projects to address these topics are defined by NCHRP, and qualified research agencies are selected from submitted proposals. Administration and surveillance of research contracts are the responsibilities of the National Academies and TRB.

The needs for highway research are many, and NCHRP can make significant contributions to solving highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement, rather than to substitute for or duplicate, other highway research programs.

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FOREWORD

Highway administrators, engineers, and researchers often face problems for which information already exists, either in documented form or as undocumented experience and practice. This information may be fragmented, scattered, and unevaluated. As a consequence, full knowledge of what has been learned about a problem may not be brought to bear on its solution. Costly research findings may go unused, valuable experience may be overlooked, and due consideration may not be given to recommended practices for solving or alleviating the problem.

There is information on nearly every subject of concern to highway administrators and engineers. Much of it derives from research or from the work of practitioners faced with problems in their day-to-day work. To provide a systematic means for assembling and evaluating such useful information and to make it available to the entire highway community, the American Association of State Highway and Transportation Officials—through the mechanism of the National Cooperative Highway Research Program—authorized the Transportation Research Board to undertake a continuing study. This study, NCHRP Project 20-05, "Synthesis of Information Related to Highway Problems," searches out and synthesizes useful knowledge from all available sources and prepares concise, documented reports on specific topics. Reports from this endeavor constitute an NCHRP report series, Synthesis of Highway Practice.

This synthesis series reports on current knowledge and practice, in a compact format, without the detailed directions usually found in handbooks or design manuals. Each report in the series provides a compendium of the best knowledge available on those measures found to be the most successful in resolving specific problems.

PREFACE

By Jo Allen Gause
Staff Officer
Transportation Research Board

More than half of all traffic fatalities result from roadway departure crashes. This type of crash occurs after a vehicle crosses an edge line or centerline or otherwise leaves the traveled way. A variety of engineering strategies, often referred to as countermeasures, have been implemented by state and local agencies to prevent roadway departure crashes and reduce the severity of injuries if crashes do occur. This synthesis documents countermeasures being used by state departments of transportation to prevent roadway departure crashes.

Information for this study was gathered through a literature review and a survey of state departments of transportation. Three case examples provide examples of specific countermeasures and roadway departure programs.

Appendices A through F can be found at www.TRB.org by searching for "NCHRP Synthesis 515."

Hugh W. McGee, Sr., collected and synthesized the information and wrote the report. The members of the topic panel are acknowledged on page iv. This synthesis is an immediately useful document that records the practices that were acceptable with the limitations of the knowledge available at the time of its preparation. As progress in research and practice continues, new knowledge will be added to that now at hand.

CONTENTS

Note: Photographs, figures, and tables in this report may have been converted from color to grayscale for printing. The electronic version of the report (posted on the web at www.trb.org) retains the color versions.

SUMMARY

Practices for Preventing Roadway Departures

As reported by the FHWA, from 2013 to 2015, an average of 18,275 fatalities resulted from roadway departure crashes, which is 54% of all traffic fatalities in the United States (*1*). A roadway departure crash is defined by FHWA as a crash that occurs after a vehicle crosses an edge line or centerline or otherwise leaves the traveled way.

Roadway departure crashes result from a variety of contributing factors involving the driver, the vehicle, the highway, and the environment. Preventing these types of crashes, or reducing the injury severity if they do occur, requires a multidisciplinary approach involving engineering, enforcement, education, and emergency medical services. From the highway perspective, a variety of engineering countermeasures have been implemented by state and local transportation agencies to mitigate roadway departure crashes. For the purposes of this synthesis, an engineering countermeasure is any traffic control device (e.g., sign, signal, pavement marking), geometric design feature (e.g., shoulder, horizontal alignment, clear zone, superelevation), roadside safety hardware (e.g., guardrail, cable median barrier), or other physical change to the roadway implemented to counter a safety problem either at a spot location, a section of road, or, more broadly, within the agency's road network.

Engineering countermeasures have been used on all roadway types (from local two-lane roads to Interstate freeways) and in all area types (rural, suburban, and urban) to achieve the following objectives:

- Keep vehicles on the roadway,
- Minimize the consequences of leaving the roadway, and
- Reduce head-on and cross-median crashes.

The objectives of this synthesis project were to identify and summarize countermeasures being used by state departments of transportation (DOTs) to prevent roadway departure crashes and to identify the data-driven advantages and disadvantages of these countermeasures. More specifically, the project was to gather information on:

- Relative extent of use of the countermeasures (i.e., rarely, sometimes, often);
- Any implementation hurdles that were overcome (e.g., policy, maintenance, public feedback);
- Programmatic implementation strategies (e.g., hot spots versus systemic); and
- Agency countermeasure evaluations [e.g., before-and-after safety analysis, crash modification factors (CMFs) or system performance functions (SPFs), durability studies, life-cycle cost analysis].

The information gathering portion of the project was conducted in the following steps:

- A literature search and review—initially a preliminary literature search to identify the potential list of engineering countermeasures, and then a more complete review of published literature on the safety effects for each of the countermeasures;

- An online questionnaire sent to all 50 state DOTs and that of Washington, D.C., for the purpose of determining the countermeasures being used by those agencies and related issues; and
- Interviews with representatives in three states to develop case examples for specific successful countermeasures and roadway departure programs.

The initial literature search identified 20 countermeasures, which in turn were used as the focus of a questionnaire survey of the states' practices. The state survey also explored:

- Safety problem identification and countermeasure implementation programs being followed,
- Additional countermeasures being used,
- Evaluations of safety effectiveness of countermeasures,
- Evaluations of non-safety issues related to materials and maintenance,
- Research needs of the states, and
- Influence (if any) of emerging vehicle technologies, including autonomous vehicles.

Forty-one state DOTs responded to the questionnaire, equating to an 80% response rate. Key findings from the survey are summarized in the following.

All of the states are using the traditional high-crash-frequency or crash-rate approach (also known as the hot-spot approach) for identifying problem locations. However, most of the states are also using the systematic and/or systemic approaches. Both are considered especially effective for implementation of low-cost countermeasures, with the former approach applying selected measures to certain crash types, and the latter approach applying applicable countermeasures to sites with high-risk roadway features correlated with severe crash types.

Most of the states were using all of the 20 countermeasures to a varying level. Based on the responses from the survey, three additional countermeasures were identified. The countermeasures that 90% or more of the states responded they were using are:

- Shoulder rumble strips (100%),
- Centerline rumble strips (98%),
- Flashing beacon on warning signs (98%),
- Tree removal (98%),
- Increased sight distance on curves (93%),
- Superelevation improvement (93%),
- High-friction surface treatment (90%), and
- Cable median barriers (90%).

The other part of the equation is how frequently the states used a particular countermeasure. To obtain a measure of this factor, the respondents were given three choices: often, sometimes, and rarely. Without any guidance on what amount of application in terms of miles or number of locations should be assigned to each choice, wide variations among the respondents should be expected. With that caveat, the survey revealed that shoulder rumble strips were being used often by 85% of the states. Other countermeasures being used often, at a level greater than 50%, were SafetyEdge (63%), edge-line rumble strips (59%), cable median barriers (57%), and centerline rumble strips (55%).

Those countermeasures that have been shown to be especially effective in reducing roadway departure crashes or their severity include:

- Shoulder, edge-line, and centerline rumble strips,
- SafetyEdge,
- High-friction surface treatment,
- Cable median barriers,

- Increasing the clear zone,
- Flattening side slopes, and
- Increasing sight distance for curves.

The use of the first four countermeasures has become so widely accepted as effective that some states are now integrating them into their design guidelines with criteria as to where they should be deployed.

Agencies were given the opportunity to raise any other issue related to the application of countermeasures for roadway departure crashes. Two issues raised were:

- Unsafe driving behaviors such as speeding, distraction, fatigue, and driving under the influence of alcohol or drugs are major contributing factors to roadway departure crashes. Many of the engineering countermeasures being used can target these behaviors, but the use of enforcement and education strategies should be included as part of a comprehensive safety program.
- It is sometimes difficult to convince local road owners (e.g., towns, small counties) to deploy even low-cost signs and marking countermeasures. A systemic approach that identifies high-risk areas is seen as a method for justifying such countermeasures. An overall push to implement as many of the systemic countermeasures as possible as part of a maintenance program was considered a long-term solution to bringing down the total number and severity of roadway departure crashes.

One of the items in the questionnaire to the states was "indicate which of the countermeasures that your state is using need more research." The collective responses from the states indicated that further research is needed for nearly all of the countermeasures. While the specific scope of the research was not specified, the states wished to be sure that a certain countermeasure would bring about a reduction in roadway departure crashes and/or a reduction in serious injuries and fatalities. Furthermore, they would like to know if a countermeasure is cost-effective in order to justify the expenditure, especially for the more costly countermeasures. These two basic research needs suggest the need for a comprehensive research program that systematically conducts research on the countermeasures. Ideally, for each countermeasure, the following would be addressed:

- The safety effect in terms of changes in crashes and severity, with a goal of developing CMFs that could be posted in the CMF Clearinghouse;
- The determination of non-safety impacts, such as public acceptance, life-cycle costs, and maintenance issues, so that the cost-effectiveness of the countermeasures can be determined; and
- Guidance for conditions under which the countermeasure is best suited or, on the contrary, should not be used.

CHAPTER 1

Introduction

Background

As reported by the FHWA, from 2013 to 2015, an average of 18,275 fatalities resulted from roadway departure crashes, which is 54% of all traffic fatalities in the United States for those years (*1*). A roadway departure crash is defined by the FHWA as a crash that occurs after a vehicle crosses an edge line or centerline or otherwise leaves the traveled way (*1*).

Roadway departure crashes result from one or more of a variety of contributing factors involving the driver, the vehicle, the highway, and the environment. Prevention of these types of crashes, and reducing the injury severity if they do occur, requires a multidisciplinary approach involving engineering, enforcement, education, and emergency medical services. From the highway perspective, a variety of engineering countermeasures have been implemented by state and local transportation agencies to mitigate roadway departure crashes. Engineering countermeasures have been used on all roadway types (from local, two-lane roads to Interstate freeways) and in all area types (rural, suburban, and urban) to achieve the following objectives:

- Keep vehicles on the roadway,
- Minimize the consequences of leaving the roadway, and
- Reduce head-on and cross-median crashes.

Before proceeding, the term "countermeasure" needs to be defined. In the highway safety literature, the terms "objectives," "strategies," "treatments," and "countermeasures" are used separately and at times interchangeably. In the *Highway Safety Manual* (HSM), the term "countermeasure" is used throughout Chapter 3. While not formally defined in the HSM, the following statements are made:

> *CMFs [crash modification factors] are generally presented for the implementation of a particular treatment, also known as a countermeasure intervention, action, or alternative design. Examples include illuminating an unlighted road segment, paving gravel shoulders . . .* (*2*)

The Crash Modification Factors (CMF) Clearinghouse defines a countermeasure as:

> *For road safety engineers . . . typically a physical change to the infrastructure of a road section or intersection, such as the addition of signs, signals, or markings, or a change in roadway design.* (*3*)

For the purpose of this synthesis, an engineering countermeasure is any traffic control device (e.g., sign, signal, pavement marking), geometric design feature (e.g., shoulder, horizontal alignment, clear zone, superelevation), roadside safety hardware (e.g., guardrail, cable median barrier) or other physical change to the roadway implemented to counter a safety problem either at a spot location, section of road, or, more broadly, within an agency's road network.

Synthesis Objective

The highway safety literature is robust concerning the development and evaluation of these countermeasures, but what has not been surveyed and documented is the state of the practice among the state departments of transportation (DOTs) for their use or non-use. Therefore, the stated objectives of this synthesis project were to identify engineering countermeasures being used by state DOTs to prevent roadway departure crashes and also to identify their data-driven advantages and disadvantages. The synthesis was to focus on enhancements, treatments, and improvements of existing roads. The information to be gathered was to include:

- Countermeasures organized by the three objectives mentioned previously;
- Relative extent of use (i.e., rarely, sometimes, often);
- Conventional and innovative countermeasures;
- Implementation hurdles that were overcome (e.g., policy, maintenance, public feedback);
- Programmatic implementation strategies (e.g., hot spots versus systemic); and
- Agency countermeasure evaluations [e.g., before-and-after safety analysis, CMFs or system performance functions (SPFs), durability studies, life-cycle cost analysis].

Approach

The information gathering portion of the project was conducted in the following steps:

- A literature search and review—initially a preliminary literature search to identify the potential list of engineering countermeasures, and then a more complete review of published literature for each of the countermeasures that focused on their safety effectiveness.
- An online questionnaire sent to all 50 state DOTs and that of Washington, D.C., for the primary purpose of identifying the countermeasures being used by those agencies and their experiences with them. There were 41 agencies that responded, equating to an 80% response rate.
- Follow-up interviews with representatives of three states, which served as case examples for roadway departure safety programs and for specific countermeasures' successes.

Report Contents

The contents of the remaining chapters are as follows:

- Chapter 2 documents the identification of the initial list of countermeasures that served as the focus for the state DOT survey of practices.
- Chapter 3 presents the results of the survey questionnaire. A large portion of this chapter is devoted to the states' practices for each of the identified countermeasures.
- Chapter 4 documents the key findings, conclusions, and suggestions for future research.

The appendices (which are available at www.TRB.org by searching for "NCHRP Synthesis 515") include the following:

- Appendix A presents the questionnaire sent to each state but condensed to reduce the page length.
- Appendix B contains 33 tables that show the responses from the states for each of the questions.
- Appendix C is the Massachusetts Lane Departure Crash Data Analysis, which illustrates how one state identifies roadway departure crashes.
- Appendix D is a case study document that describes how Arizona used the performance-based practical design approach to evaluate two safety roadside departure crash countermeasures—widening shoulders and improving superelevation.
- Appendix E is a project case study on high-friction surface treatments from Kentucky.
- Appendix F provides information about noteworthy programs being conducted by three states—Alabama, Georgia, and North Carolina—for the implementation of countermeasures.

CHAPTER 2

Engineering Countermeasures for Roadway Departure Crashes

Engineering countermeasures for roadway departure crashes have been deployed by state agencies for several decades, and new countermeasures continue to be developed by industry and state agencies. In order to establish the state of the practice among the states for use of engineering countermeasures, it was first necessary to identify those countermeasures. To that end, two key resources were reviewed—the *AASHTO Strategic Highway Safety Plan*, including the *NCHRP Report 500* series, developed under the direction of AASHTO, and the FHWA's Office of Safety website. This chapter presents the results of this effort and concludes with a list of countermeasures included in the survey questionnaire.

AASHTO Strategic Highway Safety Plan and *NCHRP Report 500* Series

In 1998, AASHTO approved the *AASHTO Strategic Highway Safety Plan*, which identified 22 emphasis areas to pursue in order to significantly reduce highway crash fatalities. That plan was revised and updated in 2005 (*4*). The Highway Safety Plan serves as an overview document that presents the 22 key emphasis areas and the strategies within each that should be undertaken to achieve a safety goal of reducing the fatality rate on the nation's highways. The plan has three emphasis areas directly relevant to the safety issue of roadway departure crashes:

1. Keeping vehicles on the roadway,
2. Minimizing the consequences of leaving the road, and
3. Reducing head-on and across-median crashes.

The Highway Safety Plan references a series of guides, prepared under NCHRP with the overall title of *NCHRP Report 500: Guidance for Implementation of the AASHTO Strategic Highway Safety Plan*, corresponding to the emphasis areas. Each guide, identified as a volume in the series, includes a brief introduction, a general description of the safety problem, the strategies and countermeasures to address the problem, and a model implementation process. Three guides that are relevant to this synthesis are:

- *Volume 3: A Guide for Addressing Collision with Trees in Hazardous Locations* (*5*),
- *Volume 4: A Guide for Addressing Head-On Collisions* (*6*), and
- *Volume 6: A Guide for Addressing Run-Off-Road Collisions* (*7*).

An initial listing of engineering countermeasures can be found in these guides. Table 1, prepared from Exhibit I-1 in Volume 6, lists several strategies—a term used in these guides interchangeably with "countermeasures"—for three objectives for the run-off-road emphasis area.

Table 1. Run-off-road objectives and strategies (7).

Objective	Strategies
Keep vehicles from encroaching on the roadside	Install rumble strips
	Install edge-line "profile marking," edge-line rumble strips, or modify with narrow or no paved shoulders
	Install mid-lane rumble strips
	Provide enhanced shoulder or in-lane delineation and marking for sharp curves
	Provide improved highway geometry for horizontal curves
	Provide enhanced pavement markings
	Provide skid-resistant pavement surfaces
	Apply shoulder treatments: • Eliminate shoulder drop-offs • Widen and/or pave shoulders
Minimize likelihood of crashing into object or overturning if vehicle travels off the shoulder	Design safer slopes and ditches
	Remove/relocate objects in hazardous locations
	Delineate trees or utility poles with retroreflective tape
Reduce the severity of a crash	Improve design of roadside hardware
	Improve design and application of barrier and attenuation systems

Volume 3 of the *NCHRP Report 500* series discusses strategies for addressing collisions with trees in hazardous locations (*5*). The report presents two objectives for addressing this problem: (1) prevent trees from growing in hazardous locations, and (2) eliminate the hazardous condition and/or reduce the severity of the crash. A "hazardous condition" is not explicitly defined in the guide, but it would likely include any area within the required clear zone for the road type, along the roadside within a horizontal curve section, or any location where there is a cluster of run-off-road crashes. The strategies for addressing these two objectives are found in Table 2.

Table 2. Objectives and strategies for addressing crashes with trees in hazardous locations (5).

Objective	Strategies
Prevent trees from growing in hazardous locations	Develop, revise, and implement planting guidelines to prevent placing trees in hazardous locations
	Mowing and vegetation control guidelines
Eliminate hazardous condition and/or reduce severity of a crash	Remove trees in hazardous locations
	Shield motorists from striking trees
	Modify roadside clear zone in vicinity of trees
	Delineate trees in hazardous locations

Table 3. Objectives and strategies for addressing head-on crashes (6).

Objective	Strategies
Keep vehicles from encroaching into opposite lane	Install centerline rumble strips for two-lane roads
	Install profiled thermoplastic strips for centerline
	Provide wider cross-sections on two-lane roads
	Provide center two-way, left-turn lanes for four- and two-lane roads
	Reallocate total two-lane roadway width (lane and shoulder) to include a narrow buffer median
Minimize the likelihood of crashing into an oncoming vehicle	Use alternating passing lanes on four-lane sections at key locations
	Install median barriers for narrow-width medians

Volume 4 of the *NCHRP Report 500* series discusses strategies and countermeasures for addressing head-on collisions. A head-on crash typically occurs when a vehicle crosses a centerline or a median and crashes into a vehicle traveling in the opposite direction. As stated in the Volume 4 guide, the objectives of reducing the number of head-on fatal crashes are to:

- Keep vehicles from encroaching into the opposite lane,
- Minimize the likelihood of a car crashing into an oncoming vehicle, and
- Reduce the severity of crashes that occur.

The strategies (also considered as countermeasures) suggested in that guide for these three objectives are shown in Table 3.

FHWA Office of Safety

The FHWA's Office of Safety maintains a website that provides a wealth of information on all aspects of highway safety (*8*). Its comprehensive program, in part, focuses on three areas that have been identified as providing the greatest potential to reduce highway fatalities using infrastructure-oriented improvements: roadway departures, intersection crashes, and pedestrian/bicycle crashes. As noted earlier, roadway departure crashes alone account for over 50% of the fatalities, are related with intersections for another 4.4%, and are related with pedestrian/bicyclist crashes for 1.3%.

A section of the website is devoted to roadway departure safety (*1*). In that section, the FHWA notes that its efforts are guided by the Roadway Departure Strategic Approach and Plan, which involves implementing countermeasures that address roadway departure crashes that fall into three main categories or objectives:

1. Keep vehicles on the roadway,
2. Provide for safe recovery, and
3. Reduce crash severity.

The countermeasures that are included within these three categories are highlighted in the following.

Keep Vehicles on the Roadway

For this first category/objective, the following broad-level countermeasures are suggested by the FHWA:

- Adequate pavement friction,
- Rumble strips and rumble stripes,
- Horizontal curve safety, and
- Nighttime visibility.

Poor pavement conditions, especially wet pavement, have been identified as one of the major contributing factors in roadway departure crashes. Therefore, the FHWA suggests that traditional friction courses or high-friction surface treatments should be considered for curves with numerous wet-weather crashes or for severe curves with higher operating speeds (*1*).

The FHWA Office of Safety has a website dedicated to rumble strips and rumble stripes (where the edge line is placed over the rumble strip) (*9*). It references a recently completed project that provides a report by Himes et al. (*10*) that documents the policies and practices of several state DOTs for their use of rumble strips and rumble stripes; the report has an accompanying Decision Support Guide (*11*).

For the general countermeasure of horizontal curve safety, the FHWA notes that:

> *. . . about three-quarters of curve-related fatal crashes involve single vehicles leaving the roadway and striking trees, utility poles, rocks, or other fixed objects—or overturning. Most roadway departure countermeasures are effective when applied specifically at horizontal curves. A focus on horizontal curves can prove to be a cost-effective approach to reducing roadway departure crashes* (1).

At the website, the reader is pointed to a report entitled *Low-Cost Treatments for Horizontal Curve Safety 2016* (*12*), which documents numerous countermeasures:

- Longitudinal pavement markings:
  - Centerline, and
  - Edge line.
- Delineators.
- Advance markings for curves:
  - Speed advisory markings in lane, and
  - Speed reduction markings (also known as optical speed bars).
- Basic signing countermeasures:
  - Advance warning signs,
  - Advisory speed plaques,
  - Combination curve/intersection signs,
  - Supplemental devices in a curve,
  - Combination horizontal alignment/advisory speed signs,
  - Chevron alignment signs, and
  - One-direction large arrow signs.
- Enhanced signing countermeasures:
  - Larger devices,
  - Doubling-up devices,
  - Retroreflective strips on sign posts,
  - High retroreflective and fluorescent sheeting, and
  - Flashing beacons.
- Dynamic curve warning systems.

- Skid-resistant pavement countermeasures:
  - High-friction surface treatments,
  - Pavement grooving, and
  - Superelevation.
- Shoulder countermeasures:
  - Shoulder widening,
  - Shoulder paving,
  - SafetyEdge, and
  - Rumble strips and rumble stripes.
- Roadside improvements:
  - Clear zones,
  - Slope flattening,
  - Roadside barriers, and
  - Delineation on barriers.

For each of these countermeasures (with a few exceptions), the report discusses their design, application guidelines, safety effectiveness, and relative cost (low, medium, or high).

For the nighttime visibility countermeasure, the FHWA has a separate Nighttime Visibility website that contains information about three areas that affect nighttime visibility: adequately maintained retroreflective signs, pavement markings, and roadway lighting (*13*). Specific countermeasures are not presented, however.

Provide for Safe Recovery

For the second objective, the FHWA notes that three general countermeasures are effective for assisting drivers in recovering safely:

- Shoulders,
- Safe pavement edges, and
- Clear zones.

Shoulders are a common geometric design element for highways, and their design features are found in AASHTO design guides and state design policies and manuals.

To mitigate vertical drop-offs at the pavement edge, the FHWA advocates installing SafetyEdge—a paving technique where the edge is shaped at approximately 30 degrees from the pavement cross slope. Its website has several pages devoted to this specific countermeasure, including case examples from several states.

A clear zone is defined as an unobstructed, traversable roadside area that allows a driver to stop safely or regain control of a vehicle that has left the roadway. Design guidelines for the width of the clear zone can be found in AASHTO and state DOT design manuals. Within this countermeasure group is removal of or protection from trees and utility poles and other roadside hardware that is not considered crashworthy.

Reduce Crash Severity

Reducing the severity of a crash is the third objective of FHWA's Roadway Departure Strategic Approach and Plan. As noted previously, providing an adequate clear zone for the road type should eliminate what could be an injury-producing roadway departure crash. However, road hardware such as sign and luminaire supports and delineator posts are often placed within the clear zone, and because of the terrain, often a sufficient clear zone cannot be provided within reasonable costs. In the former case, these devices are designed to be crashworthy, meaning that

Table 4. Countermeasures used for three objectives for reducing the occurrence and severity of roadway departure crashes.

COUNTERMEASURE		OBJECTIVE		
Type	Description	Keep Vehicles on Roadway	Minimize Consequences of Leaving Roadway	Reduce Head-On and Cross-Median Crashes
Traffic control device	Wider edge line	✓		
	Advance curve warning pavement marking	✓		
	Speed advisory marking in lane	✓		
	Speed reduction marking	✓		
	Dynamic curve warning system	✓		
	Flashing beacons on warning sign	✓		
	Shoulder rumble strip	✓		
	Edge-line rumble stripe	✓		
	Centerline rumble stripe			✓
	Raised (profiled) pavement marking	✓		✓
Pavement improvement	SafetyEdge	✓		
	High-friction surface treatment	✓		
	Pavement grooving	✓		
Roadside measure	Cable median barrier		✓	✓
	Tree removal		✓	
	Increase clear zone		✓	
	Flatten side slope		✓	
Geometric design	Shoulder widening on curved section	✓		
	Increase sight distance on curve	✓		
	Superelevation improvement	✓		

they are much less likely to cause an injury if hit. If they cannot be, then they are shielded by safety barriers (e.g., guardrails, concrete barriers) or crash cushions, which can be considered countermeasures.

List of Countermeasures for State Survey

The previous discussion of countermeasures from two primary sources—the *NCHRP Report 500* series and the FHWA Office of Safety—has identified numerous countermeasures related to preventing roadway departure crashes and reducing their severity should they occur. From those, 20 countermeasures were selected for the survey of the states' practices; these are shown in Table 4. They are grouped under four categories: traffic control device, pavement improvement, roadside measure, and geometric design, and they are arrayed under three objectives: keep vehicle on the roadway, minimize the consequences of leaving the roadway, and reduce head-on and cross-median crashes. The questionnaire also provided the opportunity to identify any additional countermeasures that were being used by the states.

CHAPTER 3

Survey of the State of the Practice

Survey Questionnaire

For this synthesis, a questionnaire was sent to DOTs in all 50 states and the District of Columbia. The questionnaire, shown in Appendix A in a condensed form, was organized into five parts. Part I was used to obtain information about the person who responded. Parts II through V contained 34 questions, grouped as follows:

- Part II related to how state DOTs identify roadway departure crash problem locations and programs for selecting and implementing engineering countermeasures.
- Part III had questions relevant to the states' use (or non-use) of each of the 20 countermeasures listed in Table 4, plus questions relevant to identifying new countermeasures, states' evaluations of countermeasures, and their need for additional research.
- Part IV had two questions to explore how states were addressing vehicle-based technologies, including vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), and autonomous vehicles, as they relate to preventing roadway departure crashes.
- Part V had two questions—one to inquire if the state had a particular countermeasure that representatives wanted to feature as an effective countermeasure and another to provide an opportunity to make any further comments related to the application of countermeasures.

Forty-one states responded to the survey questionnaire. A complete tabulation of all the responses by state for each question is provided in a series of tables in Appendix B. For many of the questions, there are hyperlinks to files provided by the state. These files have various content, including policies, specifications, drawings, reports, and other relevant technical material, all of which add to the information library for the roadway departure crash issue. They were reviewed, and relevant information was extracted and included in the discussion that follows.

The remainder of this chapter will present the primary findings obtained from the state responses to the questions within Parts II through V.

Part II. Roadway Departure Problem Identification and Implementation Programs (Questions 1 Through 4)

Part II had four questions related to how states identify roadway departure crash problem locations and programs for selecting and implementing engineering countermeasures. These questions asked:

1. If the state had prepared a roadway departure safety implementation plan,
2. If the state had compiled and analyzed roadway departure crash data,
3. If the state had developed any SPFs for roadway departure, and
4. Which implementation strategy (i.e., hot spot, systematic, or systemic) the state followed.

The responses to these questions are shown in Tables B1 through B4 in Appendix B and are summarized in the following sections.

Roadway Departure Safety Implementation Plans (Question 1)

The FHWA has a safety initiative entitled "Focused Approach to Safety" whereby it provides resources to eligible high-priority states to address the nation's most critical roadway safety challenges, one of these being roadway departure crashes. Since 2009, as part of this initiative, the FHWA, through a contractor and in conjunction with the states, has developed Roadway Departure Safety Implementation Plans (RDSIPs) for 18 participating states. The state-tailored plans include systemic implementation of low-cost engineering treatments aimed at specific crash sub-types. The plans include recommended roadway departure countermeasures, a set of strategies with deployment levels, and an estimate of the funding needed to achieve a substantial and cost-effective annual reduction in roadway departure fatalities (see https://safety.fhwa.dot.gov/fas/ for further explanation and a sample RDSIP).

The first question posed to the states was to determine whether they had prepared an RDSIP; they were asked to provide a link to it if one was available. Twenty-one states responded positively, with 11 providing hyperlinks to their RDSIPs or a similar document (see Table B1 in Appendix B). These states were those from the list of 18 participating states noted previously.

This synthesis does not summarize and analyze the contents of these RDSIPs. However, they do serve as a resource of engineering countermeasures that those states felt should be implemented to address their data-driven crash problems for roadway departure crashes. For example, Arkansas's RDSIP identified the following countermeasures to be deployed to address its roadway departure crash problem:

- Enhanced signs and markings, including:
  - Oversized advance curve warning signs mounted on both left and right,
  - Chevrons,
  - Advisory speed plates beneath the advance warning signs,
  - Additional strategies to reduce high-end approach speeds (e.g., speed feedback signs, peripheral transverse pavement markings),
  - Raised thermoplastic markings, and
  - Wider edge lines.
- Centerline, edge-line, and shoulder rumble strips.
- Alignment delineation.
- Wet-weather treatments, including:
  - High-friction surfaces, and
  - Pavement grooving.
- Guardrail upgrades (*40*).

Each of the states' RDSIPs were reviewed to see if any state included a countermeasure not already mentioned; none had.

Roadway Departure Crash Data (Question 2)

The intent of question 2 was to ascertain whether (and if so, how) state DOTs have compiled and analyzed crash data related to roadway departures. Table B2 in Appendix B shows the responses of each state to this question. Thirty-six of the 41 states responding replied "yes" (meaning that they had compiled roadway departure crash data), and of those, 12 provided a link to their crash data and, if available, analysis and report. While the roadway departure crash analyses of several states could be used as examples, the analysis from Massachusetts is provided in Appendix C.

An initial task of analyzing roadway departure crash data is to extract the relevant crashes from the statewide total crash database. This requires defining what constitutes a roadway departure crash and the data elements that capture the relevant crash records. Page 8 from the Massachusetts's analysis (see Appendix C) shows its lane departure definitions and those from the Fatality Analysis Reporting System maintained by NHTSA.

Safety Performance Functions for Roadway Departure Crashes (Question 3)

SPFs are statistical models used to estimate the average crash frequency for a specific site type (with specified base conditions) based on traffic volume and roadway segment length. SPFs are developed through statistical regression modeling using historical crash data. They could also be developed for a crash type such as roadway departure crashes. Across the country, SPFs have been developed for a variety of analysis purposes. The predicted number of crashes calculated using SPFs is instrumental for a number of activities in the project development process, including (1) network screening, (2) countermeasure comparison, and (3) project evaluation. More information about SPFs can be found in a number of resources, including the *Highway Safety Manual* (*2*) and the website for the CMF Clearinghouse (*3*).

Ten states responded that they had developed SPFs that could be used for the three purposes stated previously relevant to roadway departure crashes; their responses are shown in Table B3 in Appendix B. However, only four states provided hyperlinks to documents that provide that information. And, upon review of those documents, none of the states had developed an SPF specifically for roadway departure crashes.

Programmatic Problem Identification and Implementation Strategies (Question 4)

At the national level, the Highway Safety Improvement Program (HSIP) has encouraged a traditional approach of improving roadway safety at specific high-crash locations by identifying and analyzing individual crashes at the locations, defining crash patterns, determining appropriate countermeasures to reduce future crash potential, and implementing those countermeasures. This approach is frequently referred to as the hot-spot (meaning high-crash-frequency or crash-rate) approach. Two additional approaches were being used to complement the traditional hot-spot approach:

- In the **systematic approach**, the first step is to identify low-cost countermeasures applicable to certain crash types. Then the crash data system is searched to identify highway sections that have targeted crashes at or above a crash threshold that would ensure cost-effective deployment of these countermeasures.
- The **systemic approach** involves widely implemented improvements (i.e., countermeasures) based on high-risk roadway features (e.g., no or narrow shoulders) correlated with specific severe crash types (e.g., roadway departure). It involves identifying the problem, screening and prioritizing candidate locations, selecting countermeasures, and prioritizing projects. It begins by looking at system-wide crash data to analyze and identify systemic safety problems. It then moves to a micro-level risk assessment of locations across the network, which then leads to selecting relevant countermeasures most appropriate for broad implementation. An example of how one state—Arizona—applied a systemic approach on two-lane rural highways with higher potential for run-off-road crashes is presented in Appendix D. This is an example of developing a performance-based practical design for shoulder width and superelevation, two countermeasures discussed in this report.

All 41 states responded that they follow at least two of the approaches, with many following all three; the full results are shown in Table B4 in Appendix B. Six states responded that they also use other approaches; three are noted here:

- Sites are identified through network screening and further refined through road safety audits (Alabama).
- The United States Road Assessment Program (usRAP) is used as a systemic safety analysis tool to characterize crash risk (Utah—see http://www.usrap.org/ for information about this tool, which is sponsored by the Roadway Safety Foundation).
- Safety management plans, which look at segments of roads with hot spots; this approach applies consistent improvements throughout the length of the chosen corridor (Nevada).

Part III. Countermeasures Being Used by State Departments of Transportation (Questions 5 Through 24)

For questions 5 through 24 (see the survey questionnaire in Appendix A), the states were asked, for each countermeasure shown in Table 4, if they used that countermeasure. If they replied "yes," they were asked how frequently they used it, with choices of rarely, sometimes, and often. Guidance was not offered as to what level of use (e.g., number of sites or mileage) would apply to the three frequency levels. If they replied "no," they were asked to provide a reason, with options being:

1. Not aware of the countermeasure,
2. Countermeasure not proven to be effective,
3. Insufficient funding,
4. Negative public feedback,
5. Maintenance concerns, or
6. Any other reason.

They were also asked to provide any documents relevant to a policy or guideline, as well as for any comments.

The responses to the use of these 20 countermeasures by each of the 41 states are provided in Tables B5 through B24 in Appendix B. In this section, the key findings of the states collectively will be presented for each countermeasure. Each countermeasure will be described, followed by the most recent findings of their safety effectiveness from previous literature, followed by a summary of state practices as identified from the questionnaire responses. Noteworthy comments from individual states regarding the use or non-use of the countermeasures are highlighted as well.

Edge-Line Widths Greater Than the Standard 4 In. (Question 5)

Description

Edge-line pavement marking defines or delineates the edge of the roadway. It provides a visual reference to guide motorists and helps reduce drifting onto the shoulder and roadside area. According to the *Manual on Uniform Traffic Control Devices* (*14*), the standard width for a normal line is 4 to 6 in., and a wide line is considered to be at least twice the width of a normal line. Typically, edge lines, especially on non-freeways, are 4 in. wide. Increasing the width provides a better visual perspective and signifies a heightened degree of emphasis. Figures 1 and 2 show the same road section with a 4-in. edge line and an 8-in. edge line, respectively.

Figure 1. Roadway with 4-in. edge line (12).

Figure 2. Roadway with 8-in. edge line (12).

Literature Findings

The most recent and comprehensive research on wider edge lines has given evidence of their safety benefits. In their 2013 report, Carlson et al. (*15*) cite the following percent reductions in crash types based on data from three states as evidence of the safety benefit of this countermeasure:

- Total crashes: 15.0% to 30.1%,
- Fatal and injury crashes: 15.4% to 37.7%,
- Day crashes: 12.0% to 29.1%, and
- Night crashes: –2.4% to 30.7%.

State Practices

The responses from the 41 states are shown in Table B5 in Appendix B. Thirty-one states stated that they used this countermeasure, and as shown in Table 5, 12 used it often, 10 sometimes, and nine rarely, with 10 states indicating that they did not use this countermeasure. (Note: For this table through Table 21, the first column shows the number of states that responded to the question, the last column shows the number of states that indicated they did not use the

Table 5. States' responses on use of wider edge lines.

Total States Responding	By Frequency of Use			Do Not Use
	Often	Sometimes	Rarely	
41	12	10	9	10

particular countermeasure, and the middle three columns show frequency of use. Not all states that responded that they used the countermeasure provided a response as to the frequency of use; hence, for some countermeasures, the sum of the frequency of use and "do not use" will not add to the total number of states responding.)

The states that responded that they did not use wider edge-line markings had the following reasons:

- Not aware of countermeasure (one state),
- Countermeasure not proven to be cost-effective (four states),
- Insufficient funding (two states),
- Maintenance concern (two states), and
- Other (six states).

Some of the comments provided for not using this countermeasure were:

- "Do not believe wider lines to have the advantage claimed."
- "Wider lines make the shoulder look like a bike lane."
- "Currently prefer to ensure nighttime reflectivity rather than increasing width [of the line]."

Advance Curve Warning Pavement Marking (Questions 6, 7, and 8)

Description

Roadway departure crashes occur most frequently within highway curve sections. One of the low-cost countermeasures being used is to place some type of warning as a pavement marking in advance of the curve. This countermeasure can take different forms. Questions 6, 7, and 8 in the survey (see Appendix A) asked about three types of in-lane pavement markings:

1. Advance curve warning pavement marking, such as illustrated in Figure 3.
2. Speed advisory marking in the lane, such as illustrated in Figure 4, which displays "CURVE-55-MPH."
3. Speed reduction pavement marking to encourage speed reduction, such as the optical bar illustrated in Figure 5.

Figure 3. Example of a curve warning pavement marking (16).

Figure 4. Example of speed advisory marking (12).

Literature Findings

The literature review did not uncover any studies that reported on the effectiveness of these measures in terms of changes in crashes, nor are they listed in the CMF Clearinghouse. However, Albin et al. (*12*) cite the following regarding the effectiveness of speed advisory pavement markings in reducing motorists' speeds:

> NCHRP Report 600: Human Factors Guidelines for Road Systems *(17) found that the "Curve-55-MPH" text reduced speeds on a rural road by 4 mph citing research by Chrysler and Schrock (18). Another study (19) referenced in* NCHRP Report 600 *tested the curve arrow with "SLOW" text on a suburban road and found it reduced the percentage of drivers exceeding the speed limit by more than 5 mph during the daytime and late-night timeframes.*

With regard to the speed reduction marking device (i.e., optical bars), Albin et al. (*12*) cite two studies (*20, 21*) that demonstrated the speed reduction benefit, and one study (*22*) that showed minor changes in speeds that were inconsistent.

State Practices

Tables B6, B7, and B8 in Appendix B show the state responses for the advance curve warning marking, the speed advisory marking, and the special pavement marking to encourage speed reduction countermeasures, respectively. A summary of the responses from the states for each of these three countermeasures is presented here:

- **Advance curve warning pavement marking**: Only 11 of the 41 states responded that they used this countermeasure, with only two responding with "often," and the remaining nine responding with "rarely." The primary reasons for not using this marking were:
  - Maintenance concerns, specifically the need to re-mark frequently to ensure visibility, and

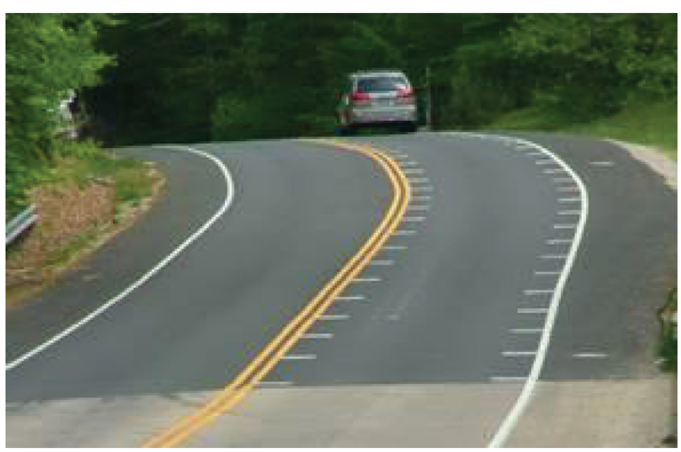

Figure 5. Example of optical speed bar marking (12).

- Concern about vehicles and motorcycles sliding on the markings, particularly if thermoplastic is used.

Three states stated that they felt signs could be more effective, and one state commented that it preferred to use other countermeasures such as doubling-up signing, fluorescent sheeting, and sign-mounted flashers.

- **Speed advisory marking in lane:** Only nine of the 41 states stated that they used this measure, and all of these states indicated that it was rarely used. The reasons raised for not using this measure included:
  - Maintenance requirements, as noted previously,
  - Concerns about vehicles such as motorcycles sliding on markings, particularly if they are long-life markings such as thermoplastic, and
  - Preference for using warning and regulatory signing.
- **Special pavement marking to encourage speed reduction:** Twenty-two of the 41 states responded that they were using or had used this type of marking, but all stated that they did so rarely. Comments from four states concerning their experiences appear to confirm the literature findings:
  - "Pilots [were tried] on a two-lane secondary (shoulder) and four-lane undivided highway. Probably will be replaced with next overlay due to limited success on speed reductions."
  - "This is a spot treatment that has been used rarely. I believe the [FHWA] ELCSI Pooled Fund Study determined these to have limited safety benefit, so we do not push for their installation."
  - "We utilize the speed reduction markings shown in the MUTCD [*Manual on Uniform Traffic Control Devices*]. We have installed these at three locations throughout the state with mixed results."
  - "We've experimented with optical speed bars with hit-and-miss success."

  As with many pavement markings subject to heavy traffic, maintaining this device at a high level is a maintenance issue. Some comments shed doubt on the cost-effectiveness of this device [such as "Showed an initial change in driver behavior (speed reduction) but not long term"], and two states responded that they tried it but that it did not seem to be effective.

  One respondent said the state preferred to use alternate countermeasures such as speed feedback signs.

Dynamic Curve Warning System (Question 9)

Description

Another countermeasure for preventing roadway departure crashes on highway curves is identified generically as a dynamic curve warning system, which can have different forms using supplemental beacons or messages that activate when a motorist approaches the curve at a high speed. Examples of two of these are shown in Figures 6 and 7. Another system that has gained more use recently is the sequential dynamic curve warning system (SDCWS), which is a series of horizontal curve chevron signs with solar-powered flashing lights embedded in the signs, as shown in Figure 8. It was this system that was suggested by question 8 in the survey.

Literature Findings

The purpose of these systems is to reduce vehicle speeds in horizontal curves, and Albin et al. (*12*) cite several studies that have shown that they do (*23, 24, 25*). With respect to the SDCWS, Smadi et al. (*26*) also showed a speed reduction and a simple before–after crash reduction of 7% to 91% at seven locations.

Figure 6. Example of a speed warning actuated sign (12).

Figure 7. Example of a dynamic warning system (12).

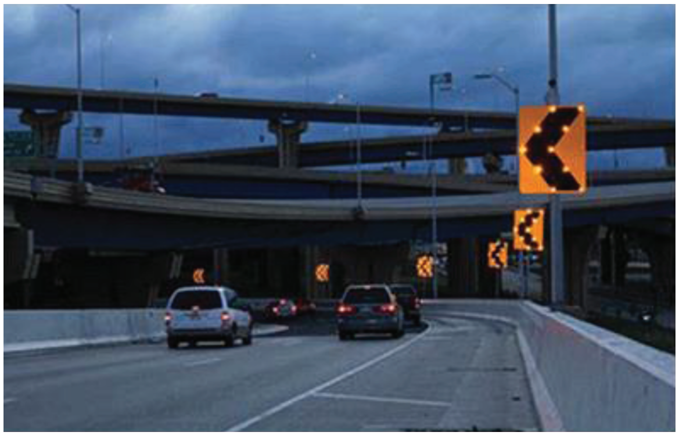

Figure 8. Example of sequential dynamic curve warning system (12).

Table 6. States' responses on use of dynamic curve warning systems.

Total States Responding	By Frequency of Use			Do Not Use
	Often	Sometimes	Rarely	
41	0	7	18	16

State Practices

Table B9 in Appendix B displays the responses from the 41 states that responded, and Table 6 summarizes these. Twenty-five states indicated that they used this countermeasure, but over half of them stated that it was rare that they did so.

The reasons the other states gave for not using this countermeasure were:

- Maintenance concerns (seven states).
- Insufficient funding (three states).
- Countermeasure not proven to be effective (two states).

Comments from two states were:

- "Power source and upkeep of the devices are typically a concern with these treatments, as most districts will shy away from the use of solar devices, as they tend to get stolen."
- "Would want to identify criteria for consideration of this countermeasure; otherwise, they would be requested at any location where there was a serious crash, regardless of the cause."

Flashing Beacons on Warning Sign (Question 10)

Description

As specified in the MUTCD (*14*), flashing beacons can be placed over warning signs to increase their conspicuity and heighten the degree of warning to the motorist. These can be as simple as adding a continuous flashing beacon to an advance curve warning sign or using one that is activated by a motorist traveling at higher than the designated speed, which is usually that shown on the speed advisory plaque; an example of the latter is shown in Figure 9.

Figure 9. Example of flashing beacon on warning sign, Augusta, ME (12).

Table 7. States' responses on use of flashing beacons on warning signs.

Total States Responding	By Frequency of Use			Do Not Use
	Often	Sometimes	Rarely	
41	9	19	12	1

Literature Findings

The literature search did not reveal any studies of the safety effectiveness of this countermeasure, but as cited by Albin et al. (*12*), when flashing beacons are installed with curve warning signs and chevrons, the CMF Clearinghouse lists a 37% to 76% reduction in various crashes based on a 2009 study from Italy (*27*).

State Practices

The responses of all states are shown in Table B10 in Appendix B. As noted in Table 7, all but one state responded that they used this countermeasure, with 12 responding with "rarely," and the remaining 28 responding with "sometimes" or "often."

The two comments shown here would seem to reflect the states' use of this countermeasure:

- "These are installed on a case-by-case basis after a thorough engineering study."
- "This is a spot treatment that is used when standard traffic control devices have proven to be ineffective in solving the problem."

The one state that responded that it did not use this device indicated that maintenance concerns were the reason.

Rumble Strips (Questions 11, 12, and 13)

Description

There are three types of rumble strips used to alert drivers that they:

1. Are about to encroach into opposite-direction traffic (the centerline rumble strip),
2. Have reached the right side of their travel lane (the edge-line rumble strip), and
3. Have encroached onto the shoulder (the shoulder rumble strip).

When the centerline or edge-line pavement marking is placed over the strip, it is referred to as a rumble stripe. Examples of these are shown in Figures 10, 11, and 12. In the questionnaire, the states' uses of these three applications were treated separately, but they are combined for this summary.

This countermeasure has become commonplace over the last two decades. It originated with shoulder rumble strips used for Interstates, and in the last 10 to 15 years has expanded to other road types, with the use of centerline rumble strips for two-lane roads and shoulder and edge-line rumble strips for non-freeway roads.

Literature Findings

The literature on all aspects of rumble strips is extensive. The FHWA has a website devoted to rumble strips (*9*). Part of the website discusses the safety effectiveness of these three types of rumble strips. It states the following:

> *Eleven states and one national study have analyzed the effectiveness of centerline rumbles in reducing crashes. These studies conclude that crossover crashes were reduced 18% to 64%, with most studies showing 40% to 60%.*

(Courtesy of Tracy Lovell, Kentucky Transportation Cabinet).

Figure 10. Example of a milled centerline rumble stripe.

(Courtesy of Tracy Lovell, Kentucky Transportation Cabinet).

Figure 11. Example of a milled edge-line rumble stripe.

(Courtesy of Tracy Lovell, Kentucky Transportation Cabinet).

Figure 12. Example of a milled shoulder rumble strip.

On rural freeways, edge-line rumble strip studies show that single-vehicle run-off-road fatal and injury crashes can be reduced by nearly 29%.

For shoulder rumbles, 14 state and two multistate studies report reductions in single-vehicle run-off-road freeway crashes of 14% to 80%, with most reporting reductions in the 30% to 40% range. The three states that restricted their crash analysis to crashes caused by distracted or drowsy driving (the true target crashes for rumble strips) report 40% to 80% reduction in those crashes. (9)

State Practices

Tables B11, B12, and B13 in Appendix B show the state responses for shoulder rumble strips, edge-line rumble strips, and centerline rumble strips, respectively. Table 8 combines the responses from the 41 states that responded regarding their use. As seen by the data, nearly all states used centerline rumble strips, a large majority were using shoulder and edge-line rumble strips, and all three types were used often by a majority of states.

Some of the comments made by the states for each of the types are shown here:

- Shoulder:
  - "Often used on divided highways; seldom used on conventional roads due to noise complaints."
  - "Policy is to install on rural limited-access and have on some urban limited-access roadways. Having difficulty making more systemic or systematic due to noise concerns."
  - "Typically, any major roadway, new or reconstruction, would include shoulder rumbles in rural locations."
- Edge line:
  - "We really like this one because of the added benefit of improved visibility of striping." [Note that this would apply to the rumble stripe design.]
  - "Used when shoulder width insufficient for milled rumble strip."
  - "Some concerns over conflicts/interactions with bicyclists."
  - "Standard practice for all rural paving projects."
- Centerline:
  - "Most districts have concerns about the reduced life span of the centerline pavement joint with CLRS [centerline rumble strips]. Districts typically prefer when this treatment is used that HSIP funds cover an overlay, as well, which is cost prohibitive."

Raised (Profiled) Pavement Marking (Question 14)

Description

A raised (also known as profiled) thermoplastic pavement marking is a less costly but less effective treatment to produce the same result from that of a centerline or edge-line rumble strip. As illustrated by Figure 13, it is a pavement marking line composed of a thicker-than-usual thermoplastic with ridges added at a prescribed spacing. This design and material increase its visibility and produce a vibration, albeit less than that of a rumble strip, to alert motorists. It is not used in states where there is snow because it is easily damaged by snowplowing operations.

Table 8. States' use of shoulder, edge-line, and centerline rumble strips.

Rumble Strip type	Yes, Use	Frequency of Use		
		Rarely	Sometimes	Often
Shoulder	41	3	3	35
Edge line*	30	7	5	17
Centerline	40	5	13	22

*One state did not indicate its frequency of use.

Figure 13. Example of profiled pavement marking (12).

Literature Findings

While this device has been used by some states for many years, there had not been any published research evaluating its effect on crashes until an FHWA-sponsored study was completed. The study used data from two-lane and multilane roads in two states—Florida and South Carolina—to examine the effects for specific crash types, including total, fatal plus injury, run-off-road, head-on, sideswipe-opposite-direction, sideswipe-same-direction, wet-road, nighttime, and nighttime wet-road crashes. Only nighttime wet-road crashes, the principal target crash type, experienced a material change in yielding a CMF of 0.908, which was not unexpected since this was the primary target crash type. Although the estimated CMF was based on a small sample of crashes and was not statistically significant at the 95% confidence level, it was consistent between the two states, which suggests the use of this device may be justifiable (*28*).

State Practices

The responses for all 40 states that responded are shown in Table B14 in Appendix B, and Table 9 shows the tally for frequency of use.

Sixteen of the states reported that they used this device, and nearly 44% (seven states) of those said they did so often. While various reasons were given for not using this device, the most prominent response was maintenance concerns—specifically that they are scraped off by snow-plows. However, in states where this is not an issue, the thicker thermoplastic material provides a longer service life than that of standard pavement markings.

SafetyEdge (Question 15)

Description

Pavement edge drop-off on highways has been linked to many serious crashes, including fatal collisions. To mitigate vertical drop-offs, the FHWA advocates installing the SafetyEdge paving technique during paving or resurfacing projects. This countermeasure allows drivers who drift off highways to return to the pavement safely (*29*).

Table 9. States' responses on use of raised profile markings.

Total States Responding	By Frequency of Use			Do Not Use
	Often	Sometimes	Rarely	
40	7	5	4	24

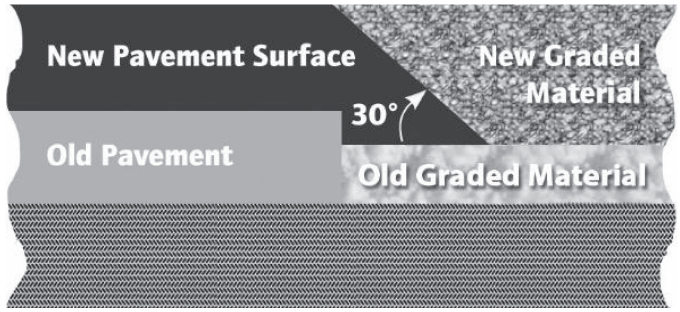

Figure 14. Cross-section showing SafetyEdge (29).

The SafetyEdge is constructed with a paver attachment that enables the pavement edge to be paved and compacted to a finished 30-degree angle to promote a safe return to the travel lane after a roadway departure. After paving, the SafetyEdge is backfilled and graded flush with the paved surface. Where the compacted material covering the pavement SafetyEdge settles or erodes, the angled edge is easily traversable by vehicles attempting to re-enter the roadway when compared to a vertical or near-vertical pavement edge drop-off (*29*). Figure 14 shows a typical pavement cross-section with the SafetyEdge for a pavement resurfacing project.

Literature Findings

The most recent and comprehensive evaluation of the safety benefits of SafetyEdge was conducted by Donnell et al. (*30*). Their study estimated CMFs for this paving technique on two-lane rural roads. Using an empirical Bayes observational before–after evaluation, they found that this countermeasure was associated with statistically significant reductions in fatal and injury (FI), run-off-road (ROR), opposite-direction, and drop-off-related crashes. Furthermore, their economic evaluation found that the SafetyEdge paving technique is cost-effective, with the benefit–cost ratios ranging from 590:1 to 1180:1 for ROR crashes and from 730:1 to 1460:1 for FI crashes.

State Practices

Table B15 in Appendix B displays the responses from all states. The use of SafetyEdge is becoming more prevalent in the United States, as evidenced by the responses summarized in Table 10, which shows that 85% of the 41 states responding were using this treatment, with a majority stating it as being used often. Several states have adopted it as part of their design standards and guidance, especially for resurfacing projects. Table B15 provides hyperlinks to several state policies, standards, and specifications

Six states responded that they had not yet adopted this paving technique because of insufficient funding, maintenance concerns, or negative public feedback. One state responded that it was working to incorporate this procedure into its standard practice but was receiving some resistance from contractors based on liability.

Table 10. States' responses on use of SafetyEdge.

Total States Responding	By Frequency of Use			Do Not Use
	Often	Sometimes	Rarely	
41	22	9	4	6

Figure 15. Shoulder widening on the inside and outside of the curve (12).

Shoulder Widening on Curved Section (Question 16)

Description

Shoulders, which can be either paved or non-paved but are usually stabilized, provide an opportunity for an encroaching vehicle to return to the travel lane. They are an integral part of the cross-section design, with recommended widths that vary depending on several factors, but notably the roadway type (see **https://safety.fhwa.dot.gov/geometric/pubs/mitigationstrategies/chapter3/3_shoulderwidth.cfm**).

Shoulder widening (depicted in Figure 15) was identified as a countermeasure for roadway departure crashes by Albin et al., who noted that it "… is particularly important in horizontal curves where vehicles typically use more of the travel lane than in straight sections" (*12*). Hence, providing a shoulder where one did not exist or, more commonly, widening an existing narrow shoulder, will provide a recovery area, allowing the driver to regain control in the event of a roadway departure.

Literature Findings

While the safety effects of varying shoulder widths have been examined for decades, the literature search did not identify any studies specific to widening shoulders on curves. The most recent relevant safety information is reported in the *Highway Safety Manual* (*2*) and presented with modification in Albin et al. (*12*) and Table 11.

Table 11. Percent change in crashes relative to providing a 6-ft shoulder on rural, two-lane roadway segments (modified from HSM, Table 13-7).

Shoulder Width	Average Annual Daily Traffic (AADT) (vehicles/day)		
	<400	400–2,000	>2,000
0 ft	+10%	Between +10% and +50%, depending on AADT	+50%
2 ft	+7%	Between +7% and +30%, depending on AADT	+30%
4 ft	+2%	Between +2% and +15%, depending on AADT	+15%
6 ft	0%	0%	0%
8 ft or more	–2%	Between –2% and –13%, depending on AADT	–13%

Crash types: Single-vehicle run-off-road, multiple-vehicle head-on, opposite-direction sideswipe, and same-direction sideswipe.

Table 12. States' responses on use of shoulder widening on curve sections.

Total States Responding	By Frequency of Use			Do Not Use
	Often	Sometimes	Rarely	
41	3	17	10	11

Earlier in this chapter, under the section Programmatic Problem Identification and Implementation Strategies, an example was presented of how Arizona applied performance-based practical design as a decision-making approach and evaluation for a shoulder width (and superelevation) improvement project as a countermeasure to a high occurrence of roadway departure crashes. In that case study, provided in Appendix D, Arizona analyzed the effect on safety for two widening alternatives (1 ft to 5 ft and 1 ft to 8 ft) on a 24-mile corridor of a two-lane rural road. It was found that while both alternatives would result in a significant reduction in total crashes, the first alternative was selected for full application because of its higher benefit–cost ratio.

State Practices

The responses from the states are shown in Table B16 in Appendix B. As shown in Table 12, 30 of the 41 states responded that they widened shoulders on curves, with 10 responding that it was rarely done, 17 that it was sometimes done, and three that it was done often.

Some of the comments from those states that responded positively were:

- "Typically, it has been done more in the past for erosion control issues rather than safety."
- "Plan on doing more in the future through systemic process."
- "We have done shoulder widening around curves to mitigate truck off-tracking issues."
- "Would be done as part of a paving project."

The reasons states gave for not using this countermeasure were varied:

- Not aware of countermeasure (two states),
- Countermeasure not proven to be effective (two states),
- Insufficient funding (four states),
- Maintenance concerns (one state), and
- Insufficient right-of-way, especially on more rural roads (one state).

High-Friction Surface Treatment (Question 17)

Description

A roadway must have an appropriate level of pavement friction to ensure that drivers are able to keep their vehicles safely in the lane. Poor pavement conditions, especially wet pavement, have been identified as one of the major contributing factors in roadway departure crashes. When a pavement surface is wet, the level of pavement friction is reduced, and this may lead to skidding or hydroplaning. To address this problem, state agencies are using several pavement friction enhancement treatments, one of which is labeled as high-friction surface treatment (HFST).

HFST products consist of a thin layer of binder—usually urethane, silicon, or epoxy—topped with specially engineered, durable, high-friction aggregates. The aggregate systems have a long-lasting skid resistance, and also make the pavement overlay much more resistant to wear and polishing. An example of an application, with a close-up of the surfaces, is shown in Figure 16.

Figure 16. Example of HFST (12).

Literature Findings

The safety benefit of this countermeasure has become well established, as reported by Albin et al. (*12*) and the FHWA website for this countermeasure (see **https://safety.fhwa.dot.gov/roadway_dept/pavement_friction/high_friction/**). Kentucky used this countermeasure on 30 curves in 2009 and observed a crash reduction of 70% to 75% at these curves. A case study report from Kentucky for this countermeasure is provided in Appendix E.

State Practices

Table B17 in Appendix B provides the responses of all 41 states. The use of this pavement treatment as a countermeasure has become widespread among the states, as shown by the summary of states' use or non-use in Table 13. Ninety percent of the 41 states responding indicated that they were using this countermeasure. Several states responded that they were starting to experiment with this countermeasure. For example, Indiana DOT was executing its first HFST projects in fiscal year 2017, investing roughly $1 million, almost exclusively for horizontal curves. It planned to continue the program in future years.

There is still some hesitancy by a few states to use this countermeasure, with one state citing insufficient funding and another questioning its durability.

Pavement Grooving (Question 18)

Description

Grooving is a pavement treatment in which narrow grooves are saw cut into the pavement surface, typically in the direction of traffic, and typically 0.75 in. apart (see Figure 17). The

Table 13. States' responses on use of HFST.

Total States Responding	By Frequency of Use			Do Not Use
	Often	Sometimes	Rarely	
41	3	17	17	4

Figure 17. Example of pavement grooving (12).

grooves increase pavement macrotexture, thereby increasing or restoring pavement friction. Grooving is typically used on concrete pavements, but it can be used on asphalt pavements (*31*). It is especially effective in reducing wet-weather crashes by improving the drainage characteristics, thereby serving as a roadway departure countermeasure.

Literature Findings

Albin et al. cited a New York State DOT evaluation of pavement grooving that found that wet-pavement–related crashes were reduced by 55%, and the total for both wet and dry pavement crashes was reduced by 23% (*12*); however, a reference was not provided. Under the FHWA's Evaluation of Low-Cost Safety Improvements Pooled Fund Study, Merritt et al., employing an empirical Bayes before–after methodology, evaluated the effects on various crash types on several types of pavement friction improvements, including diamond grooving. For diamond grooving, there was an overall benefit (significant at the 5% level) for both wet- and dry-road crashes, which resulted in a significant overall benefit for total crashes (*31*).

State Practices

The state responses for this countermeasure are shown in Table B18 in Appendix B. As shown in Table 14, 39 states responded, with a nearly equal number responding with yes and no. Of those who used this countermeasure, the majority responded with "rarely."

Two noteworthy comments from those states that used this countermeasure were:

- "Both HFST and pavement grooving have been used in areas where a significant proportion of crashes are wet-pavement–related."
- "Not part of a safety program but part of pavement group repair strategies."

Table 14. States' responses on use of pavement grooving.

Total States Responding	By Frequency of Use			Do Not Use
	Often	Sometimes	Rarely	
39	2	7	10	20

The reasons cited by states that did not use this countermeasure included:

- Not aware of the countermeasure (10 states),
- Maintenance concerns (five states), and
- Not proven to be cost-effective (two states).

Cable Median Barrier (Question 19)

Description

As stated in a 2016 NCHRP synthesis report, generic low-tension cable barriers had been used in several states for many years, and it was not until the year 2000 that a high-tension cable barrier was first installed in the United States (*32*). The questionnaire in this synthesis did not label this countermeasure as "high-tension," but based on the responses, the respondents presumably assumed that it was.

The most common applications today are in medians of divided roadways. Cable barriers function by capturing or redirecting impacting vehicles to prevent these vehicles from intruding into the opposing traffic lanes. As such, it is a countermeasure with the objective of preventing head-on crashes with opposing traffic. There are five propriety high-tension cable barrier systems deemed eligible for federal funding by the FHWA (*32*); Figure 18 illustrates one of these.

Literature Findings

The overall safety benefit from the use of cable median barrier systems has been well documented by several studies. A summary of these studies was documented by the Louisiana Department of Transportation in its *Cable Median Barrier Systemic Review* (*33*). The conclusion drawn from the many before-and-after studies of changes in crashes and severities is that these systems are highly effective in reducing fatal and severe injury crashes, but result in an increase in total, property damage only, and minor injury collisions.

State Practices

Responses from all states are shown in Table B19 in Appendix B. As shown in Table 15, all but four states responded that they used cable median barriers, with 32 responding with either "sometimes" (11 states) or "often" (21 states).

Figure 18. Example of a high-tension cable median barrier system (32).

Table 15. States' responses on use of cable median barriers.

Total States Responding	By Frequency of Use			Do Not Use
	Often	Sometimes	Rarely	
41	21	11	5	4

Some of the comments provided by the states are summarized here:

- The results of a study of high-tension cable barriers, completed by Wayne State University (*34*), show that cable median barriers have been highly effective at reducing crossover crashes in Michigan. After the barriers were installed, crossover crash rates on those freeway segments fell by 87%, and the barriers successfully contained 97% of the vehicles that hit them. Cable barriers have improved overall safety at the locations where they have been installed. The most serious crashes—fatal and severe injury crashes—decreased by 33% after cable median barriers were installed, according to statistical analysis. Since their installation, cable median barriers are estimated to have saved 20 lives and prevented over 100 serious injuries in Michigan.
- About half of one state's 1,200 centerline miles of the Interstate system have cable median barriers.
- They are implemented on high-volume and narrow-median stretches. Minnesota currently has about 500 miles implemented.

The reasons given by the four responding states for not using this barrier type were maintenance concerns (three states) and that the crash frequency was deemed to not be a significant issue.

Increase Clear Zone (Question 20)

Description

AASHTO's *Roadside Design Guide* defines a "clear zone" as the total roadside border area, starting at the edge of the traveled way, available for safe use by errant vehicles (*35*). This area may consist of a shoulder, a recoverable slope, a non-recoverable slope, and a clear run-out area. The desired minimum width is dependent on traffic volumes, speeds, and roadside geometry. By creating a clear zone, roadway agencies can increase the likelihood that a roadway departure will result in a safe recovery rather than a crash and can mitigate the severity of any crash that might occur. The AASHTO guide provides suggested values for the design clear zone, which can be from at least 7 ft to as much as 30 ft. The question posed in the survey was about increasing the clear zone beyond the minimum required.

State Practices

The responses of 39 states can be seen in Table B20 in Appendix B. As shown in Table 16, 22 states responded that they do increase clear zones beyond what would be required, with 13 replying with "sometimes," seven with "rarely," and only two with "often."

Some comments from states that responded that they used this countermeasure were:

- "Designers are encouraged to remove large hazards beyond the clear zone. This can often be difficult and hard to get approval [for]."

Table 16. States' responses on increasing clear zones.

Total States Responding	By Frequency of Use			Do Not Use
	Often	Sometimes	Rarely	
39	2	13	7	17

Table 17. States' reasons for not increasing clear zones as a countermeasure.

Reason	No. of States Citing Reason
Not aware of countermeasure	2
Countermeasure not proven to be cost-effective	2
Insufficient funding for countermeasure	9
Negative public feedback	5
Maintenance concerns	3
Other	5

- "The designer may choose to increase the clear-zone width on the outside of horizontal curves where accident histories indicate a need or where specific site investigation shows a definitive accident potential. This may be cost-effective where increased banking or other accident countermeasures are not feasible."
- "This is not used that often but is used where there is sufficient ROW [right-of-way] and crash data to support [it]."

The reasons given by states for not using this countermeasure are shown in Table 17; the primary reason was insufficient funding. Increasing the clear zone usually requires obtaining more ROW, which can increase the project cost substantially. One state's comment was "many times the project type, repaving, for example, is not scoped for acquiring the necessary ROW to increase the clear zone." From the reasons cited and from the comments received, the cost of acquiring additional ROW limits the use of this countermeasure.

Flatten Side Slope (Question 21)

Description

Steeper and cut-type slopes are more hazardous and have been shown to significantly affect the severity of run-off-road crashes. The AASHTO *Roadside Design Guide* (*35*) considers side slopes steeper than 1V:3H as critical slopes, meaning that a vehicle could become unstable to the point that the risk of it overturning is increased. Roadside slope improvement, or flattening, has as its objective the provision of a forgiving environment for an errant vehicle. Flatter slopes lower the likelihood of vehicles overturning.

Literature Findings

As reported by Albin et al., the CMF Clearinghouse contains several CMFs for slope flattening (*12*). Flattening side slopes from the critical slope of 1V:3H to just 1V:4H can realize a 42% reduction in injury crashes, while a side slope improvement of 1V:4H to 1V:6H can realize a 22% reduction in injury crashes.

State Practices

The responses from the 39 states that answered this question can be seen in Table B21 in Appendix B. As shown in Table 18, 30 states responded that they flattened slopes, but only three indicated that this was done often.

Table 18. States' responses on use of side slope flattening.

Total States Responding	By Frequency of Use			Do Not Use
	Often	Sometimes	Rarely	
39	3	18	9	9

Some of the comments made were:

- "Mostly done during reconstruction. Not an active program to complete this."
- "We hope to use this more in the future to help move the cable barrier from the shoulder to the center of the ditch, to help eliminate nuisance hits."
- "Typically 3R [resurfacing, restoration, rehabilitation] or widening project driven."

As for the nine states stating that they did not use the countermeasure, the reasons given were:

- Not aware of countermeasure,
- Countermeasure not proven to be cost-effective, and
- Insufficient funding.

Tree Removal (Question 22)

Description

One of the most common causes of fatal and severe injury crashes, especially on rural roads, is vehicles leaving the road and striking a fixed object. In fatal crashes involving a fixed object, trees are the objects most often struck. About 8% of fatal crashes involve crashes into trees (*5*). Elimination of trees with greater than a 4-in. diameter within what should be the clear zone for a given roadway (as illustrated in Figure 19) would be the obvious strategy or countermeasure. However, trees contribute to roadway aesthetics, and their removal evokes deep sentimental and environmental concerns among agencies and stakeholders (*5*).

Literature Findings

The literature contains few studies on the safety benefits of a tree removal program. In 2009, Clemson University researchers reported on their evaluation of roadside collision data and clear zone requirements in which trees and other fixed objects were considered (*37*). In South Carolina, trees account for 25% of all fatal crashes, compared to 8% nationally, and 72% of the tree-related crashes occurred on curve sections. Their analysis of sites with and without adequate clear zones led them to conclude that South Carolina could realize a notable decrease in fatal and injury crashes if the recommended clear zones were provided.

State Practices

The responses from 40 states that replied to this question can be seen in Table B22 in Appendix B. As shown in Table 19, all but one state responded that they used this countermeasure, with 18 doing so sometimes, 16 rarely, and four often.

Figure 19. Example of tree within clear zone (36).

Table 19. States' responses on use of tree removal.

Total States Responding	By Frequency of Use			Do Not Use
	Often	Sometimes	Rarely	
40*	4	18	16	1

*One state responded "yes" but did not indicate frequency of use.

From the comments provided by the respondents, it appears that it is difficult to get approval to remove trees and that it is done on a case-by-case basis and not through any general policy or guideline. One respondent commented that they needed better guidance on how this issue relates to speed—more specifically, at what speed levels does tree removal become more critical. The representative from the state that does not use this countermeasure commented that this is not a problem because they have a predominately desert climate.

The literature search on this issue uncovered an FHWA document entitled *Noteworthy Practices: Roadside Tree and Utility Pole Management* that provides examples of successful tree (and pole) management practices from several states (*38*).

Increase Sight Distance on Curves (Question 23)

Description

A Guide for Reducing Collisions on Horizontal Curves lists "increasing the radius of a horizontal curve" as one strategy for reducing the likelihood of a vehicle leaving its lane and either crossing the roadway centerline or leaving the roadway at a horizontal curve (*41*). Increasing the sight distance on a curved section of the road can be achieved by increasing its radius through realignment, as depicted in Figure 20. The line superimposed on the aerial image illustrates the old alignment.

Literature Findings

In a recent study of curve realignments that increase sight distance (*39*), the researchers developed CMFs for the following three crash types:

- Total crashes: 0.315,
- Injury and fatal: 0.259, and
- Run-off-road plus fixed object: 0.216.

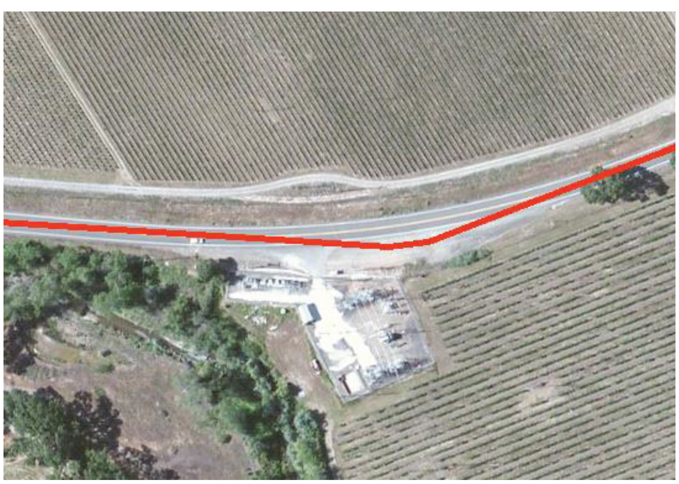

Figure 20. Example of horizontal curve realignment (39).

Table 20. States' responses on use of increasing sight distance on curves.

Total States Responding	By Frequency of Use			Do Not Use
	Often	Sometimes	Rarely	
40*	1	21	14	3

*One state responded "yes" but did not indicate the frequency of use.

They also developed CMFunctions that showed that safety benefits may be greater for curves with a larger central angle and where the difference in radius between the before and after period conditions is larger. Their economic analysis revealed a benefit–cost ratio range of 1.75:1 to 4.38:1 (*39*).

State Practices

Table B23 in Appendix B shows the responses from the states, and Table 20 shows a summary of their use or non-use. Somewhat surprisingly given the cost involved, which could include ROW acquisition, 37 of the 40 states replied that they made this improvement. Only one state indicated that it was done often, while 21 states said that it was done sometimes and 14 rarely. The most frequent comment was that this type of improvement was done on a case-by-case basis and as part of a reconstruction. The primary reason for those states not using this countermeasure was insufficient funding.

Superelevation Improvement (Question 24)

Description

Superelevation is the rotation of the pavement on the approach to and through a horizontal curve. It is intended to assist the driver by counteracting the lateral acceleration produced by tracking the curve. Selection of a maximum superelevation rate is based on variables such as climate, terrain, highway location, and frequency of slow-moving vehicles. Inadequate superelevation can cause vehicles to skid as they travel through a curve, potentially resulting in a roadway departure crash. Trucks and other large vehicles with high centers of mass are more likely to roll over at curves with inadequate superelevation. Superelevation is occasionally inadequately designed or is lost over time due to settling or overlays. Correcting an inadequate superelevation is considered a countermeasure for roadway departure crashes.

Literature Findings

The literature review did not uncover any recent studies that examined the safety effects of improving superelevation; however, the *Highway Safety Manual* provides a function for calculating CMFs for horizontal curves for two-lane rural roads based on superelevation variance (*2*).

State Practices

Table B24 in Appendix B shows the responses from all of the states, and Table 21 summarizes the responses for frequency of use. All but three of the 40 states made superelevation improvements

Table 21. States' responses on use of superelevation improvement.

Total States Responding	By Frequency of Use*			Do Not Use
	Often	Sometimes	Rarely	
40	4	15	16	3

*Two states that responded "yes" did not provide response for frequency of use.

as a roadway departure countermeasure. Based on the comments provided, this improvement appears to be done on a case-by-case basis and frequently is part of a 3R-type project.

The only reason offered for not using this countermeasure was that was not considered cost-effective.

Other Countermeasures Being Used by States (Question 25)

The intent of this question was to identify countermeasures being used by the states that were not one of the 20 mentioned in questions 5 through 24. The responses from each state are shown in Table B25 in Appendix B.

Other countermeasures obtained from the responses are:

- Passing lanes: Alaska noted that passing lanes on rural two-lane roads help with aggressive driving, which can lead to roadway departure crashes.
- Fluorescent yellow sheeting: Noted by Alabama, this device was mentioned earlier in this report, but was not included as a countermeasure because it is considered a standard traffic control device.
- Culvert extensions: Noted by Hawaii, this is a roadside improvement that might prevent rollovers or vehicles hitting a fixed object. This improvement to the roadside was also mentioned in follow-up discussions with Alabama as one of many countermeasures it was using as part of its roadway departure safety improvement program.
- LED in-pavement lighting: Noted by Colorado and by Ohio as being used on interchange ramps and rural curves.
- Motorcycle barrier attenuator: Noted by Utah, this attaches to a standard roadside guardrail to protect errant motorcyclists from impacting the guardrail post during crashes.

Research to Evaluate Safety Effectiveness of Countermeasures (Question 26)

Table B26 in Appendix B shows the responses provided by 18 states. A summary of these responses by countermeasure is as follows:

- Add 2-ft shoulder on two-lane roads:
  - Alabama – a 25% to 35% reduction.
- Rumble strips:
  - Michigan: a before-and-after crash study performed for the 2008–2010 installation locations found significant reductions across all crash severities and lane departure crash types, including:
    - 50% reduction in head-on crashes,
    - 46% reduction in run-off-road crashes,
    - 51% reduction in fatal crashes, and
    - 41% reduction in incapacitating injury crashes.
  - Mississippi: statistically significant difference in the number of roadway departures between the period before construction and the period after construction.
  - Minnesota: found no evidence to implicate centerline rumble strips as a hazard to two- or three-wheel cycles.
  - Vermont: crash analysis from the two sites evaluated demonstrated a reduction in the total number of crashes and the proportion associated with centerline crossover events.
- Cable median barrier:
  - Louisiana: cable median barriers reduced fatal and serious injury crashes by almost 30% and 20%, respectively.
  - Michigan: fatal and serious injury crashes decreased by 33%.

- Wider (6-in.) edge line:
  - Minnesota: 6-in. edge lines were an effective countermeasure for overall crash reduction and run-off-road right crash reduction.
- Slope improvement:
  - Nevada: for a single 30-mile project, simple before–after analysis in the 3-year period showed a 55% reduction in total crashes and a 75% reduction in injury crashes.
- High-friction surface treatment:
  - South Dakota: a total crash reduction of 78% over 4 years for application at four horizontal curves.

Hyperlinks to the research reports can be found in Table B26.

Countermeasures Needing More Evaluation (Question 27)

Table B27 in Appendix B displays the comments made by the 23 states that felt more research was needed for one or more of the countermeasures. The responses are summarized as follows:

- Seven states believed that more research is needed for the use of rumble strips, with concerns for:
  - Pavement maintenance for centerline rumble strips,
  - Pavement marking over the strip,
  - How or whether to use in combination with raised pavement markers,
  - Sinusoidal rumble strip effectiveness (from two states), and
  - Use with narrow shoulders.
- Three states mentioned the need for developing CMFs for tree and other fixed-object removal.
- Several states mentioned that further research was needed for delineation treatments, including for:
  - Wider edge lines,
  - Flexible tube delineators,
  - Larger (6 × 8 in.) delineators for low-volume roads, and
  - Delineation of hazards that cannot be shielded or moved.
- A few states commented on the need for further research on signing for:
  - Horizontal alignment,
  - Dynamic curve signs,
  - Higher intensity sheeting, and
  - Fluorescent sheeting.
- A few states commented on the need for further research related to shoulders, specifically:
  - Shoulder widening, and
  - Narrow-shoulder sign treatments.
- Other research needs mentioned by at least one state included:
  - Slope flattening,
  - Clear zone widening,
  - Embedded LEDs,
  - SafetyEdge, and
  - High-friction surface treatments.

Information provided in this synthesis may address some of these concerns and obviate the need for further research.

Evaluations of the Non-Safety Impacts of Countermeasures (Question 28)

The intent of this question was to determine whether there were any issues with regard to durability, service life, maintenance, or another non-safety effect for any of the countermeasures that might influence whether or how a countermeasure would be used. The comments from the

11 states that responded that they have used or intend to use the countermeasures are shown in Table B28 in Appendix B. Of note are the following:

- Georgia conducted research to determine how well pavement joints located at the center of the roadways had been holding up to centerline rumble strips. Based on that research, it was pursuing approval of a detail calling for two offset rumble strips to be placed on each side of the roadway centerline to avoid deterioration of the pavement along the joint.
- Michigan had a comprehensive analysis of its cable median barrier program performed. The sponsored research showed significant positive safety benefits from use of this countermeasure, but given the cost of installation plus considerable maintenance costs, it conducted a life-cycle cost evaluation. This evaluation consisted of a time-of-return (TOR) analysis, which is defined as the amount of time that must pass after implementation, typically gauged in years, for the expected benefits of the initiative to equal the costs of the initiative. Engineering, construction, and maintenance costs were considered as part of the TOR analysis, as well as the benefits realized by reductions in severe crashes. The evaluation revealed that the TOR for cable median barrier installation in Michigan was 13.38 years (*34*).
- Kentucky performed durability analysis of pavement markings, raised reflective pavement markers, and rumble strips as alternatives for providing wet-nighttime delineation. Some of the findings were:
  – Snow-plowable markers provided the most effective wet-nighttime delineation. Durability issues associated with the steel-casting marker made the recessed marker preferable over the life of the pavement.
  – Wet-reflective tape placed in a groove provided both dry and wet-nighttime delineation and remained durable.
  – The performance of thermoplastic material installed on the pavement surface supported its future use, but it will not provide wet-nighttime delineation. Inconsistent performance of inlaid tape argues against its expanded use. Poor performance showed that future use of wet-reflective tape should not be considered.
  – A cost analysis, considering durability of the materials, showed that the cost of using more durable materials over the life of the pavement was not dramatically more than the cost of traffic paint.
  – Edge-line rumble stripes and centerline rumble strips enhanced wet-nighttime delineation and should be incorporated into resurfacing projects on two-lane roads where pavement width permits.
- Both Virginia and Washington were evaluating the life cycle of their high-friction service treatment sites.

Part IV. Questions Related to Vehicle-Based Technologies (Questions 30 Through 31)

While the scope of this synthesis was to focus on engineering countermeasures, states were asked to comment on how they were addressing two vehicle-based technologies—(1) V2V and V2I technologies, and (2) autonomous vehicles. While these are not engineering measures, it was suggested to explore how these vehicle technologies might affect states' programs for addressing the roadway departure crash problem. These were meant to be exploratory questions and were not intended to be part of an in-depth inquiry.

Actions States Pursuing Related to V2V and V2I Technologies (Question 30)

Thirty-five states answered this question, with 15 responding that they took no special action, six simply providing a contact person for follow-up, and 15 responding with a variety of comments, which are shown in Table B30 in Appendix B. The responses from those states that provided more substantive information are highlighted here:

- "We have created a Transportation, Systems, Management and Operations Division to incorporate new technology and develop programs" (Connecticut).
- "Multidisciplinary team meeting to discuss and determine actions needed for future implementation" (Kentucky).
- "We have formed an Autonomous Vehicle Technology Team, which is investigating issues that affect this technology" (Louisiana).
- "We are watching this evolution closely and watching for those infrastructure improvements that may be required, such as wider edge lines or Lidar sensing units along the roadway" (Nevada).

The responses indicate that states were mostly monitoring these technologies and assessing what actions would be necessary with regard to roadway infrastructure.

Actions States Are Pursuing Related to Autonomous Vehicles (Question 31)

This question asked what special actions were being taken by states to ensure that lane boundaries [defined by lane lines (for multilane facilities), edge lines, or centerlines] were well defined. For this question, 16 states provided a response; these are shown in Table B31 in Appendix B. In general, based on these 16 responses and the fact that the remaining 24 states did not provide a response, it appears that states were not taking any special actions at the time. The responses from these two states would seem to apply to most of the states:

- "Future of automated and autonomous vehicles has not to this point changed the manner in which we establish and maintain those traffic control devices."
- "Simply applying our pavement marking policy and doing our best to maintain the longitudinal markings. But we were doing this before autonomous vehicles."

Part V. Case Examples and Final State Comments (Question 32 and Question 34)

Examples of How Countermeasures Were Effective in Reducing Roadway Departure Crashes (Question 32)

States were asked to provide examples of any countermeasures they applied that were especially effective in reducing roadway departure crashes and that they would like to see featured in the synthesis. Sixteen states responded to this question; their statements are shown in Table B32 in Appendix B. Countermeasures that some states felt had been especially effective were:

- High-tension cable median barriers,
- Shoulder widening with rumble strips,
- Rumble strips of all types, and
- High-friction surface treatments.

Comments from two state DOT respondents in support of these countermeasures are shown here:

- "Internally, the agency [Indiana] recently completed two simple before–after in-service performance studies of our now 10-year-old Interstate cable median barrier program and 4-year-old rumble stripE program. Both concluded that the two treatments were highly

effective at reducing risk of severe crashes, particularly fatal events. We expected high effectiveness (CRF [crash reduction factor]) with cable barrier relative to reducing risk of fatal crashes on freeways, but were stunned by apparent positive effectiveness of rumble stripE projects. Overall, Indiana DOT has installed some 1,300 'run-miles' of edge-line and centerline rumble stripE since 2011. In terms of highly relevant crashes to that countermeasure, of the 54 projects with sufficient 'after installation' time to make a reasonable before–after assessment, only one site experienced higher frequency of fatal crashes after vs. before. One outstanding example of sheer before–after effect was on a 17-mile stretch of high-volume, high-speed two-lane highway—one of the early projects, with combination of centerline and edge-line rumble stripe—where 11 fatal crashes took place in the 4 and a half years just prior to installation but none in the 3 years since."
- "Mississippi had a number of very serious and/or fatal cross-median crashes in 2007 on a stretch of high-speed urban Interstate in the Jackson area. One example is this story: http://www.wdam.com/story/7130388/arkansas-man-faces-murder-charge-in-fatal-i-220-wreck. This necessitated our first installation of high-tension cable barrier along this Interstate highway. Even before the system was fully constructed in 2008, the system was saving lives. From the initial success stories, MDOT [Mississippi DOT] has been able to systemically install cable barriers on all high-speed, controlled access, divided highways where the site conditions allowed the installation of this treatment. The initiative to install cable barrier through Mississippi won MDOT an award in 2012. While no countermeasure is completely crash proof, it is the belief of MDOT that this treatment has significantly reduced crashes on high-speed, controlled access, divided highways across the state."

Also, Kentucky provided a link to a project case study for its evaluation of a high-friction surface treatment; a one-page summary is provided as Appendix E. The state treated a horizontal curve that experienced 53 wet-weather crashes over a 3-year period with HFST. After the treatment, there were only five wet-weather crashes over a period of 3.18 years.

Responses to this question from three states—Alabama, Georgia, and North Carolina—were of particular interest not because of examples of effective countermeasures, but of examples of approaches they are using to further the implementation and evaluation of roadway departure countermeasures. Follow-up interviews were conducted to acquire additional information beyond what was provided in their responses shown in Table B32. Summaries of their programs are provided in Appendix F.

Other Issues Related to the Application of Countermeasures (Question 34)

For the last question, states were asked to raise any other issues related to the topic that had not been covered by responses to the other questions. Table B33 in Appendix B provides the full responses from the states that choose to respond. What is interesting in these responses is that they are all different, with no repetition among the states. Some of the states' comments are shown here:

- "An overall push to implement as many of the systemic measures as possible as part of maintenance or new construction is likely the most effective long-term solution to bringing down the total number and severity of crashes."
- "Driver inattention, fatigue, DUI, etc. are major contributing factors."
- "We need to address the noise issue that influences the use of standard rumble strips."
- "Driveways and embankments are a huge issue—yet very costly to fix on a systematic basis."
- "Due to our small number of crashes on local roads and low volumes, it is difficult sometimes to convince towns that chevrons and curve signs should be installed. We are working

on a new systemic approach that we hope will help us identify high-risk areas and provide justifications."

- "Many facets of continuing superelevated shoulders adjacent to the roadway or having a sloped rollover, namely:
  - Sensitivity of various slope rollovers (2%, 4%, 6%, 8%),
  - Effects of slope rollover location with respect to total shoulder width and paved shoulder width,
  - Effects of slope rollover with respect to interaction with roadside crash barrier, and
  - Effects of slope rollover with respect to roadway slopes outside of shoulder."

CHAPTER 4

Conclusions

Findings

Primary objectives of this project were to identify countermeasures that state DOTs were using to prevent the occurrence of roadway departure crashes and to mitigate the severity of crashes should they occur. Within those overall objectives, the project was to identify the extent of countermeasure application, the effectiveness of the countermeasures, issues that could hamper their application, and research needed to address any concerns about their use. The information needed to meet these objectives was obtained from a literature search and review as well as a survey of the state DOTs' practices using an online questionnaire. The survey was distributed to all 50 states and the District of Columbia, with 41 agencies responding. A summary of the key findings from this effort are presented in the following.

Roadway Departure Problem Identification and Implementation Programs

Roadway departure crashes—defined by the FHWA as crashes that occur after a vehicle crosses an edge line or centerline or otherwise leaves the traveled way—account for over 50% of all traffic fatalities nationwide. This significant safety issue was recognized in the *AASHTO Strategic Highway Safety Plan* developed in 1998 and has carried forward in subsequent highway safety programs at the federal DOT level—through the FHWA's Roadway Departure Strategic Approach and Plan—and at the state DOT level through state strategic highway safety plans.

The survey of the state DOTs revealed that nearly half of the 41 states responding had prepared formal roadway departure implementation plans that recommended installation of low-cost engineering countermeasures. Most states responded that they were using a variety of problem identification and implementation approaches, including:

- Traditional hot spot: applying appropriate countermeasures at locations with a high crash frequency or rate,
- Systematic: applying specific countermeasures at highway sections that have targeted crash types at or above a crash threshold, and
- Systemic: applying countermeasures (typically low cost) at locations based on roadway features correlated with specific severe crash types.

Strategies for Preventing Roadway Departure Crashes and Severity

The strategic approach to addressing roadway departure crashes is based on objectives or risk categories. The *AASHTO Strategic Highway Safety Plan* identified these as:

1. Keep vehicles from encroaching on the roadside,
2. Minimize likelihood of crashing into an object or overturning if vehicle travels off the shoulder, and
3. Reduce the severity of the crash.

The FHWA's strategic approach to effectively prevent roadway departure crashes and fatalities is structured around three objectives:

1. Keep vehicles on roadway,
2. Provide for safe recovery, and
3. Reduce crash severity.

These strategies or objectives are similar and are aimed at reducing the occurrence of a roadway departure crash and reducing the severity of a crash should it occur. Within these strategies/objectives, there are numerous engineering countermeasures.

Engineering Countermeasures Used by State DOTs

For the purpose of the state survey used for this project, 20 countermeasures were presented, with the intent of determining whether and to what extent the states were using them. Table 22 shows for each of the countermeasures included in the questionnaire the percentage of states that responded with "yes" (i.e., that they do use the countermeasure) and the percentage that replied with "often," "sometimes," and "rarely." Unless otherwise indicated, the percentages shown are based on 41 states responding. Observations from this table are:

- The countermeasures for which 90% or more of the 41 states replied "yes" are:
  - Shoulder rumble strip (100%),
  - Centerline rumble strip (98%),
  - Flashing beacon on warning signs (98%),
  - Tree removal (98%),
  - Increase sight distance (94%),
  - Superelevation improvement (93%),
  - High-friction surface treatment (90%), and
  - Cable median barrier (90%).
- At the other end of the scale, only two countermeasures showed less than 30% of states responding that they were used:
  - Advance pavement markings for curves (27%), and
  - Speed advisory marking in lane (22%).

The other part of the equation is how frequently the states were using a particular countermeasure. To obtain a measure of this factor, the respondents were given three choices: often, sometimes, and rarely. Without any guidance on what amount of application in terms of miles or number of locations should be assigned to each choice, wide variations among the respondents were expected. With that caveat, from the table it can be observed that shoulder rumble strips were being used often by 85% of the states. Other countermeasures being used often, at a level greater than 50%, were SafetyEdge (63%), edge-line rumble strips (59%), cable median barriers (57%), and centerline rumble strips (55%).

Table 22. Frequency of use of countermeasure by states.

Countermeasure		Percent of States Responding (%)*			
		Use Counter-measure	Frequency of Use		
			Often	Sometimes	Rarely
Traffic control devices	Wider edge line	76	39	32	29
	Advance curve warning pavement marking	27	18	0	82
	Speed advisory marking in lane	22	0	0	100
	Speed reduction marking	54	0	0	100
	Dynamic curve warning system	61	0	28	72
	Flashing beacons on warning sign	98	23	47	30
	Shoulder rumble strip**	100	85	8	7
	Edge-line rumble stripe	75	59	17	24
	Centerline rumble stripe	98	55	32	13
	Raised (profiled) pavement markings**	40	44	31	25
Pavement improvements	SafetyEdge	85	63	26	11
	High-friction surface treatment	90	8	46	46
	Pavement grooving***	49	10	37	53
Roadside measures	Cable median barrier	90	57	30	13
	Tree removal**	98	10	48	42
	Increase clear zone***	56	9	59	32
	Flatten side slope***	77	10	60	30
Geometric measures	Shoulder widening on curved section	73	10	57	33
	Increase sight distance on curve**	94	3	58	39
	Superelevation improvement**	93	11	43	46

Notes:

*Percentage based on 41 states responding unless otherwise indicated.
**Percentage based on 40 states responding.
***Percentage based on 39 states responding.

The survey responses identified the following additional countermeasures:

- **Passing lanes:** Alaska noted that passing lanes on rural two-lane roads (which are common in that state) helped with aggressive driving, which can lead to roadway departure crashes.
- **Fluorescent yellow sheeting:** Used for certain advance curve warning signs.
- **Culvert extensions:** Noted by Hawaii and Alabama, this is a roadside improvement that might prevent rollovers or hitting a fixed object.
- **LED in-pavement lighting:** Noted by two states, this solar-powered delineation device has been used for interchange ramps and curves in rural areas.
- **Motorcycle barrier attenuator:** Noted by Utah, this hardware attaches to standard roadside guardrails to protect errant motorcyclists from impacting the guardrail post during a crash.

Safety Benefits of Countermeasures

The safety benefit of the identified countermeasures has been researched for the last 30 years—even longer for some. In the last decade or so, more sophisticated and reliable safety analysis tools for before–after evaluations of roadway safety countermeasures, such as the empirical Bayesian approach, have been used to more accurately estimate the change in crashes and severity resulting from a countermeasure. Crash modification factors and functions have been developed for several of the identified countermeasures; these are found in the CMF Clearinghouse (*3*). Those countermeasures that have been shown to be especially effective in reducing roadway departure crashes or crash severity include:

- Shoulder, edge-line, and centerline rumble strips;
- SafetyEdge;
- High-friction surface treatments;
- Cable median barriers;
- Increasing clear zones;
- Flattening side slopes; and
- Increasing sight distances on curves.

While these and other countermeasures have shown reductions in crashes or crash severity, there are other factors that influence their cost-effectiveness. States were asked to comment on research they had performed on non-safety impacts, such as durability, life-cycle, and maintenance needs, which would affect their overall cost-effectiveness. Countermeasures that were being evaluated for these concerns include:

- Cable median barriers,
- High-friction surface treatments,
- Wider edge lines, and
- Centerline pavement joints with centerline rumble strips.

Concerns Raised by States

States were given the opportunity to raise any other issues related to the application of countermeasures for roadway departure crashes. Two issues raised were:

- Detrimental driving behaviors such as speeding, driving under the influence of alcohol or drugs, distraction, and fatigue are major contributing factors to roadway departure crashes. Some of the engineering countermeasures, most notably rumble strips, can counteract some of these driver behaviors, but most mentioned in this report will not. Hence, comprehensive safety programs to address roadway departure crashes include enforcement and education strategies.
- It is difficult sometimes to convince local road owners (e.g., towns, small counties) to deploy even low-cost sign and marking countermeasures. A systemic approach that identifies high-risk areas is a method for justifying such countermeasures. An overall push to implement as many of the systemic countermeasures as possible as part of a maintenance program may be a cost-effective, long-term solution to bringing down the total number and severity of roadway departure crashes.

Influence of Advanced Vehicle Technologies

The emergence of autonomous vehicles as well as V2V and V2I technologies may have a profound effect on preventing all types of crashes, including roadway departure crashes. However, highway agencies may have to enhance their maintenance activities and modify their traffic control devices to accommodate these smart vehicles. For example, tracking within the travel lanes for autonomous vehicles will require that travel lanes be clearly marked, necessitating a high level of pavement marking maintenance. The development of V2I should bring about more technology for traffic control devices. To examine this issue, two questions were posed to the states concerning what actions, if any, they were pursuing in anticipation of these technologies becoming prevalent on their highway systems. Responses from the states indicated that they had begun to address these issues, albeit in an embryonic stage. For example, Nevada's response ("We are watching this evolution closely and watching for those infrastructure improvements that may be required, such as wider edge lines or Lidar units along the roadway") is reflective of several of the state responses.

Conclusions

This synthesis project was undertaken to identify and document the practices of the state DOTs in addressing the safety problem of roadway departure crashes through the implementation of engineering countermeasures. From the survey of the states, with 41 responding, and the literature review, the following general conclusions have been drawn:

- States recognize the scope and severity of roadway departure crashes and are developing programs for addressing this significant safety problem. Prevention of roadway departure crashes and reduction in their severity is recognized by states in their strategic highway safety plans and, for many states, in the development and implementation of roadway departure safety implementation plans.
- States are using alternative approaches for identifying locations for implementation of roadway departure countermeasures, including traditional high-crash (hot-spot), systematic, and systemic approaches.
- There are numerous engineering measures (e.g., traffic control devices, geometric design enhancements, pavement treatments, and safety hardware) being used to counter the occurrence of roadway departure crashes and reduce crash severity. This project identified well over 20 such countermeasures that are being deployed by the states to:
  - Keep vehicles from encroaching on the roadside or, in the case of two-lane roads, the opposing lane;
  - Minimize the likelihood of crashing or overturning if a vehicle travels off the shoulder; and
  - Reduce the severity of crashes.
- All of the identified countermeasures have been shown to be effective in reducing the occurrence of roadway departure crashes or reducing the resulting severity, but to varying degrees and levels of certainty.
- Some countermeasures, particularly the use of rumble strips, SafetyEdge, and HFST, have been integrated into state design policies with guidelines established for when they should be used.

Suggested Research

One of the questions posed to the states asked them to "indicate which of the countermeasures your state is using that need more research." The collective responses from the states indicated that further research is needed for nearly all of the countermeasures reported on in previous chapters. However, in most responses, the nature or the objective of the research was not specified. Presumably, the states wish to be sure that a certain countermeasure would bring about a reduction in roadway departure crashes or a reduction in serious injuries and fatalities. Furthermore, they likely want to know if the countermeasure is cost-effective and will justify the expenditure. These two basic research needs suggest a comprehensive research program that systematically conducts research on the countermeasures. Ideally, for each countermeasure, the following would be addressed:

- The safety effect in terms of changes in crashes and severity, with the goal of developing CMFs that could be posted in the CMF Clearinghouse;
- The determination of non-safety impacts, such as life-cycle costs, maintenance issues, and public acceptance; and
- Guidance for conditions under which the countermeasure is best suited or, on the contrary, should not be used.

Much of this information already exists for some of the countermeasures, at least in part. This information needs to be catalogued, documented, and publicized to state and local agencies.

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APPENDICES

Appendices A through F can be found at www.TRB.org by searching for "NCHRP Synthesis 515."

Abbreviations and acronyms used without definitions in TRB publications:

A4A	Airlines for America
AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FAST	Fixing America's Surface Transportation Act (2015)
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
HMCRP	Hazardous Materials Cooperative Research Program
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
MAP-21	Moving Ahead for Progress in the 21st Century Act (2012)
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
PHMSA	Pipeline and Hazardous Materials Safety Administration
RITA	Research and Innovative Technology Administration
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TDC	Transit Development Corporation
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S.DOT	United States Department of Transportation

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