OVERVIEW OF SAFETY COUNTERMEASURES FOR ROADWAY DEPARTURE CRASHES

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ABSTRACT
A roadway departure (RwD) crash happens when a vehicle leaves the traveled way (crossing an edgeline or a centerline). These crashes, comprising run-off-road (ROR) and cross-median head-on collisions, tend to be more severe than other crash types. In 2013, RwD crashes accounted for 56 percent of all motor vehicle traffic fatalities. Inattention or fatigue, an avoidance maneuver, or traveling too fast are the common reasons a driver may leave the travel lane. Roadway and roadside geometric design features (e.g., lane and shoulder widths, horizontal curvatures, sideslope, and clear zones) play a significant role in whether or not human error results in a crash. To achieve the Federal Highway Administration’s (FHWA’s) Toward Zero Deaths vision, many safety countermeasures have recently been implemented by state departments of transportation and local agencies to mitigate RwD crashes. This paper presents a summary of various case examples to provide transportation practitioners with a good understanding of the effectiveness of RwD safety countermeasures.

Keywords: Roadway Departure Crash, Safety Countermeasures, Run-off-road Crash
INTRODUCTION

A roadway departure (RwD) crash is defined by the Federal Highway Administration (FHWA) as “A crash in which a vehicle crosses an edge line, a centerline, or otherwise leaves the traveled way.” These crashes, comprising of run-off-road (ROR) and cross-median/cross-centerline head-on collisions, tend to be more severe than other crash types. The reasons for ROR events are varied and include a driver attempting to avoid a vehicle, an object, or an animal in the travel lane; inattentive driving due to distraction, fatigue, sleep, or drugs; the effect of weather on pavement conditions; and traveling too fast through a curve or down a grade. There are also a number of roadway design factors that can increase the probability that a driver error will result in an ROR crash (e.g., travel lanes that are too narrow, substandard curves, and unforgiving roadsides) (1). Most head-on crashes are similar to ROR crashes—in both cases, the vehicle strays from its travel lane (2).

RwD crashes constitute one of the most severe types of crashes. According to the FHWA, in 2013, 56 percent of all motor vehicle fatalities involved a RwD. Figure 1 depicts the percentage of total RwD fatal crashes across the United States, categorized by the first event in the crash. According to a query of seven years of crash data (2007–2013) from the Fatality Analysis Reporting System (FARS) database, an average of 57 percent of motor vehicle traffic fatalities occurred each year due to RwD in the United States (3). The distribution of this number differs between states (see Figure 2). In addition, the majority of RwD crashes occurred during the nighttime and inclement weather conditions (e.g., fog, snow).

FIGURE 1 Percentage of fatal motor crashes in the United States in 2013 (4).
FIGURE 2  Average percentage of RwD fatalities in each state (2007-2013) (4).
Several strategies to reduce the number of ROR crashes have been identified by the American Association of State Highway and Transportation Officials (AASHTO) including (5):

- Pavement edgeline installation
- Centerline and shoulder rumble strip installation
- Pavement marking enhancement
- Shoulder drop-offs elimination
- Safer slopes design
- Object removal/relocation within the clear zone
- Object delineation using retroreflective tape
- Barrier design improvement
- Horizontal curve geometric improvement
- Skid-resistant roadway surface provision

Not only are most of these strategies low-cost countermeasures but they can also be implemented systematically. This paper provides a brief easy-to-read overview of cost-effective improvements for preventing vehicle departures from roadways. It is a summary of a recent publication by the American Traffic Safety Services Association (ATSSA), which can help transportation agencies better understand the effectiveness, and prioritize the implementation of each RwD safety countermeasure.

ROADWAY DEPARTURE SAFETY COUNTERMEASURES
Countermeasure implementation case studies for mitigating RwD crashes were developed based upon a comprehensive literature review and input from state and local agencies. RwD safety countermeasures were divided into three major categories: signs, pavement safety, and roadside design. Figure 3 illustrates the 14 RwD safety countermeasures discussed in this paper.
c) Advisory Ramp Speed Sign/Chevrons
d) High Friction Surface Treatment
e) 20-foot Raised Pavement Markers
f) Edge Line Pavement Markings
g) Safety Edge
h) Milled Centerline Rumble Strips
Table 1 lists the 14 countermeasures, the evaluation method used, the results obtained, and the relevant contact agencies. As shown in the table, the percentage reduction of the total number of RwD crashes varies between 23 and 91, depending on the safety countermeasure. Similarly, for the total number of ROR crashes, the reduction ranges from 22.1 percent to 61.6 percent. Most agencies used a simple before-and-after evaluation method. Few determined benefit-cost (B/C) ratios because significant crash number reductions and the relatively low-cost countermeasures often resulted in fairly high B/C ratios.
### TABLE 1. Results from the 14 Case Studies

<table>
<thead>
<tr>
<th>Safety Countermeasure</th>
<th>Safety Evaluation Method</th>
<th>Results</th>
<th>Benefit-cost (B/C) Ratio</th>
<th>State Agency Implementation</th>
<th>Implementation Time</th>
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<tr>
<td><strong>Pavement Safety</strong></td>
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<tr>
<td>Safety Edge</td>
<td>Simple before-and-after</td>
<td>• Total crashes: -5.7 %</td>
<td>3.8 to 43.6</td>
<td>GDOT and INDOT</td>
<td>2005</td>
</tr>
<tr>
<td>Centerline Rumble Strips (CLRS)</td>
<td>Simple before-and-after</td>
<td>• Total crashes: -33.0 %</td>
<td>-31.0 %</td>
<td>Total head-one crashes: -35.0 %</td>
<td>Total opposite-direction sideswipe crashes: -46.0 %</td>
</tr>
<tr>
<td>High Friction Surface Treatments (HFSTs)</td>
<td>Simple before-and-after</td>
<td>• Total RwD crashes in wet weather: -91.0 %</td>
<td>-78.0 %</td>
<td>Total RwD crashes in dry weather: -56.0 %</td>
<td>---</td>
</tr>
<tr>
<td>Raised Pavement Markers (RPMs)</td>
<td>Simple before-and-after</td>
<td>• Total RwD crashes: -86.0 %</td>
<td>-94.0 %</td>
<td>Total injuries: -38.0 %</td>
<td>---</td>
</tr>
<tr>
<td>Edge Line Pavement Markings</td>
<td>Simple before-and-after</td>
<td>• Total RwD crashes: -23.0 %</td>
<td>-38.0 %</td>
<td>Total severe RwD crashes: -38.0 %</td>
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<tr>
<td><strong>Signs</strong></td>
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<td>Signs</td>
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<tr>
<td>Dynamic Curve Warning Systems (DCWSs)</td>
<td>Empirical Bayes (EB)</td>
<td>• Total ROR crashes: -22.1 %</td>
<td>-24.5 %</td>
<td>Total crashes during dark condition: -24.5 %</td>
<td>8.0</td>
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<tr>
<td>Advanced Curve Warning and Advisory Speed Sign</td>
<td>Simple before-and-after</td>
<td>• 2.6 mph reduction in mean speed</td>
<td>76 % of vehicle slowed down</td>
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<td>ODOT</td>
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<td>Signs</td>
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<td>Signs</td>
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</tbody>
</table>
### Shoulder Rumble Strips (SRS)
- Simple before-and-after
- **Total ROTRR crashes:** -47.0 to 61.6%
- **Total severe ROTRR crashes:** -15.3 to 66.6%

### Roadside Design

<table>
<thead>
<tr>
<th>Roadside Design</th>
<th>Simple before-and-after</th>
<th>Before: 19 fatal crashes; after: 0 fatal crash</th>
<th>---</th>
<th>MnDOT</th>
<th>2004-2008</th>
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<tr>
<td>Cable Barrier</td>
<td>Simple before-and-after</td>
<td><strong>Total severity and RwD index:</strong> -16.6 to 36.7%</td>
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<td>NCDOT</td>
<td>1997-2010</td>
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<tr>
<td>Guardrail</td>
<td>Simple before-and-after</td>
<td><strong>Total severity and RwD index:</strong> -43.7 to 69.2%</td>
<td>---</td>
<td>NCDOT</td>
<td>2002-2011</td>
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<td>Shoulder Widening</td>
<td>Simple before-and-after</td>
<td><strong>Total severity and RwD index:</strong> -16.6 to 36.7%</td>
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<td>NCDOT</td>
<td>1997-2010</td>
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<tr>
<td>Breakaway Supports for Signs and Lighting</td>
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<tr>
<td>Clear Zone Improvements</td>
<td>Simple before-and-after</td>
<td><strong>Total crashes:</strong> -38.0%</td>
<td>---</td>
<td>Iowa DOT</td>
<td>2006</td>
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</tbody>
</table>
Signs
According to the FARS database, more than 83 percent of the total RwD fatal motor vehicle crashes occur at horizontal curves (3). Enhancing curve delineation with signs is typically considered to be a low-cost safety improvement. These signs alert drivers to changes in road alignment and provide information on the actions to be taken. For example, a sign may encourage drivers to reduce their speeds. When placed and maintained appropriately, curve signage may reduce the frequency and severity of RwD crashes.

Chevrons
According to the Manual on Uniform Traffic Control Devices (MUTCD), chevrons and/or one-direction large (Figure 3a) arrows shall be used where the difference between speed limit and the advisory speed is 15 mph or more. It is important to ensure that these signs are placed and aimed properly (7). The Washington State Department of Transportation (WSDOT) conducted a safety evaluation analysis of chevron signs for 139 treated curves on rural two-lane roads. Empirical Bayes (EB) analysis results demonstrated that chevrons along horizontal curves decreased the total number of lane departures and crashes of all types during dark conditions by up to 22.1 and 24.5 percent, respectively. According to cost analysis results, chevrons are also a very cost-effective countermeasure, with a benefit-cost (B/C) ratio exceeding 8:1 (6).

Dynamic Curve Warning Systems
Dynamic curve warning systems (DCWSs) detect the speed of approaching vehicles and are programmed to provide drivers exceeding a certain speed threshold with a message, flashing light-emitting diodes (LEDs), or a display of their speed (Figure 3b). Results from a national safety study indicate that, two years after installation, a 2.0 mph mean speed reduction occurred at the beginning of the curve (8). The Oregon Department of Transportation (ODOT) installed a DCWS system in advance of a curve on Interstate 5 near Myrtle Creek in Douglas County. The system consists of a dynamic message sign, a 45-mph advisory speed sign, a controller unit, a radar unit, and computer software. The analysis results showed that 76 percent of drivers slowed down following the system’s installation, with a 2.6 mph reduction in mean speed for passenger cars (6).

Advanced Curve Warning and Advisory Speed Sign
Curve or turn warning signs are placed in advance of curves to alert drivers of what lies ahead on their route (Figure 3c). Properly installed curve warning signs have been proven to improve safety for horizontal curves. The cost for most commonly used curve warning signs with advisory speed plates ranges from $500 to $700 per sign (9). The Kentucky Transportation Cabinet (KYTC) installed an LED-enhanced curve warning sign on KY 82 in Estill County. Since its installation in 2006, no fatalities have been recorded, despite a crash history of one fatality per year for three consecutive years prior to the installation of the sign (6).

Pavement Safety
Pavement safety countermeasures can also make significant contributions to reducing the number of RwD crashes. Insufficient friction between the tire and pavement surface, poor visibility during nighttime hours, and pavement drop-off edge are factors that may contribute to a vehicle leaving the traveled way.
High Friction Surface Treatments

High friction surface treatments (HFSTs) consist of a thin layer of durable aggregates (typically calcined bauxite) that are highly resistant to polishing (10) (Figure 3d). The aggregate is bonded to asphalt, concrete, or other pavement surfaces using polymer binders. HFST is not meant to change the pavement’s structural performance. Rather, HFST provides greater friction, allowing motorists to maintain better control in dry and wet road conditions, resulting in reduced numbers of RwD crashes. According to the FHWA Every Day Counts (EDC) 2012 Initiatives, a B/C ratio of about 24:1 can be achieved by implementing pavement friction treatments (11). The KYTC launched a 3-year HFST program to enhance friction on horizontal curves at 75 locations statewide in 2010. The safety analysis results confirm that the total number of RwD crashes at the treated sites dropped by 91/78 percent in wet/dry weather conditions (6).

Raised Pavement Markers

Raised pavement markers (RPMs) are often used by transportation agencies as delineation treatments to improve nighttime visibility, particularly in wet pavement conditions (Figure 3e). According to the AASHTO’s Strategic Highway Safety Plan (SHSP), RPMs are considered to be an effective, low-cost strategy for mitigating RwD crashes (12). Assisted by the FHWA and the Alabama Department of Transportation (ALDOT), Mobile County in Alabama systematically applied RPMs along 10 rural roadways with the highest number of RwD crashes. In this project, RPMs were installed with 80-foot spacing in tangent sections of roadways, 40-foot spacing between the advanced warning curve sign and the beginning of the curve, and 20-foot spacing through the curve. Crash analysis results reveal an average annual decrease of about 86 percent for RwD crashes and about a 94-percent reduction in injuries (6).

Edge Line Pavement Markings

Edge line pavement markings (Figure 3f) distinguish travel lanes from the adjacent shoulders to delineate the travel path. According to the MUTCD, the edge line markings on the right edge of the roadway shall be white. In addition, the normal width of edge line markings is 4 to 6 inches and wide edge line markings are to be at least twice the width of a normal line (7). From 2009 to 2012, the Missouri Department of Transportation (MoDOT) initiated a program to install edge line marking on eligible high risk rural roads (HRRRs). First, MoDOT performed a safety evaluation of implemented countermeasures on 73 high-risk roadway segments. Based on the safety analysis results, the total number of RwD crashes and severe RwD crashes decreased by 23 to 38 percent following the installation of edge line markings (6).

Safety Edge

As determined by the FHWA in 2012, the Safety Edge is one of nine proven safety countermeasures (Figure 3g). This strategy mitigates the vertical elevation difference by sloping the edge of the pavement to 30 degrees during paving or resurfacing projects. A Safety Edge is installed using one of several commercially available devices that can be attached to the hot-mix asphalt (HMA) paver (13), and is also highly cost-effective. The added cost of resurfacing with this treatment was determined to be very small, because the asphalt must simply be reformed to create the Safety Edge. The Midwest Research Institute (MRI) conducted a safety evaluation of the Safety Edge at 261 treated sites (685 miles) in Georgia and 148 sites (514 miles) in Indiana. The evaluation results showed a 5.7 percent reduction in total crashes after the implementation of the Safety Edge. Additionally, the B/C ratio for two-lane highways with paved shoulders ranged
from 3.8 to 43.6 for Georgia and from 3.9 to 30.6 for Indiana. For two-lane highways with unpaved shoulders, the B/C ratio ranged from 3.7 to 62.8 for Georgia and from 2.8 to 12.8 for Indiana (6).

Centerline Rumble Strips

Centerline rumble strips (CLRS) are a longitudinal safety feature that can be installed at or near the centerline of undivided roadways (Figure 3h). CLRSs include a series of milled or raised elements on the pavement (14). Tires rolling over rumble strips generate noise and vibration which alert a distracted or drowsy driver to make a safe steering correction. The Michigan Department of Transportation (MDOT) initiated a CLRS installation program during the period from 2008 to 2010. Approximately 5,400 miles of non-freeway roadways were included in this program. The study results proved that the implementation of rumble strips resulted in a significant reduction in both center line and edge line encroachments in tangent sections and through curves (6). More specifically, after CLRS installation, the number of center line encroachments to the left side within the curves dropped by 87 percent, and there was a 33 percent reduction in all crash types. Additionally, the number of opposite-direction sideswipe collisions, multi-vehicle head-on crashes, and single-vehicle RwD crashes decreased by 46, 35, and 31 percent, respectively (6).

Shoulder Rumble Strips

Shoulder rumble strips (SRS) are commonly installed in paved shoulders that are adjacent to the travel lane (Figure 3i). Like CLRS, SRS provide acoustical and vibrational warnings to drivers who are straying from their travel lane. According to survey results from 50 state DOTs, the B/C ratio for SRSs was estimated to be approximately 50:1 (15). The WSDOT investigated the possibility of applying SRS on undivided highways. To date, WSDOT has installed over 260 miles of a mix of milled and raised SRS on its rural two-lane undivided highways. In early 2013, the WSDOT undertook a review of historical crash data over the nine years from 2002 to 2010. The study examined a total of 190 roadway miles with SRS in 45 segments, covering all geographic areas of the state (6). In cases where SRS had been added during or after CLRS installation, the results showed that run-off-road to the right side (ROTRR) crash rates were reduced by 47.0–61.6 percent for crashes of all severity types, and by 15.3–66.6 percent for fatal and serious injury crashes.

Roadside Design

The probability of the severity of ROR crashes depends on the roadside features, including sideslope, fixed-object density, offset to fixed objects, and shoulder width (16-21). Collision with a fixed object has been identified as the primary harmful event in ROR crashes (22). A recent inquiry of the FARS database revealed that 7,416 people perished in crashes involving roadside fixed objects in 2012, accounting for 22 percent of the total fatalities for that year (3). Some practical countermeasures to enhance roadside safety include roadway cross-section improvements, hazard removal or modification, and delineation. These countermeasures have been utilized in all area types (i.e., rural, suburban, and urban) to keep vehicles in travel lanes and to reduce potential collisions with roadside objects, such as trees, signs, and utility poles (1).

Cable Barrier

A barrier is a device designed to stop or redirect errant vehicles to prevent a more serious crash. Although barriers cannot reduce the total number of crashes, the benefits of cable barriers are that they tend to minimize the severity of injuries by absorbing the impact of the crash and have safer
consequence compared to vehicles striking the shielded obstacles. Flexible barriers, made from wire rope strung between posts (Figure 3j), are the most forgiving type of barriers and the best option for minimizing injuries to vehicle occupants (23). A number of high-tension cable barrier systems are available, which remain functional after a crash and may not require immediate repairs. In 2004–2008, the Minnesota Department of Transportation (MnDOT) installed cable barriers at 31 segments along approximately 150 freeway miles to reduce the number of fatalities and severe injuries caused by cross-median crashes. The safety evaluation results revealed that the number of fatal cross-median crashes and serious injury cross-median crashes after cable barrier installation dropped from 19 to 0 and 8 to 6, respectively (6).

Guardrail
Guardrails (Figure 3k) are the most common and widely used type of barrier and can be effective in reducing:

- reportable RwD crashes,
- vehicles from hitting fixed objects, and
- vehicles from going over steep embankments.

The most common guardrail system used in the United States is the metal beam guardrail, which consists of W-shaped metal beam rail elements fastened to wood or galvanized steel posts. Guardrails have a low life-cycle cost since they often remain functional without immediate need of repair (12). The North Carolina Department of Transportation (NCDOT) evaluated the results of safety and hazard elimination projects of 14 divisions in the state. Using a before-after analysis at the three treatment sites, the results showed that the percentage reduction in the total Severity Index and RwD Severity Index range from 16.6 percent to 36.7 percent. In this study, crash severity index was defined as being equal to the total number of equivalent property damage only (PDO) crashes (76.8 for “K=Fatal” and “A= Incapacitating injury” crashes, and 8.4 for “B=Non-Incapacitating injury” and “C=Possible injury” crashes) divided by the total number of crashes (6).

Shoulder Widening
Roadway shoulders, when used as a safety feature, can improve road safety not only by allowing drivers to recover in a stable, clear recovery area, but also by providing drivers with more space to maneuver to avoid crashes. In addition, a wider shoulder improves stopping sight distance (SSD) on horizontal curves and provides better bicycle accommodation (Figure 3l). Shoulder width can vary between 2 feet for minor rural roads and 12 feet for major roads. It can also be widened both inside and outside curves (24). For low-volume roads (less than 1,000 vehicles per day) with narrow pavement width (less than 12 feet), it is more effective to consider narrower lanes with a wider shoulder (25). Based on a before-after analysis of three treatment sites, the NCDOT showed reductions in the total Severity Index and RwD Severity Index ranging from 43.7 percent to 69.2 percent (6).

Breakaway Supports for Signs and Lighting
Breakaway supports (Figure 3m) refer to various devices designed and constructed to break or yield when they are hit by a vehicle (26). It is not always feasible to maintain object-free roadside clear zones (the total roadside border area starting at the edge of the traveled way); however, crash severity can be diminished by using breakaway supports for roadside objects. The 2009 MUTCD mandates that post-mounted roadside sign supports in the clear zone be breakaway, yielding, or
shielded (7). In phone interviews with traffic and safety engineers from several state DOTs regarding the safety effects of breakaway supports, most agencies reported that this countermeasure has been proven to be effective in reducing the severity of RwD crashes and that no evaluation has been deemed necessary.

Clear Zone Improvements
A clear zone is defined by the 2011 Roadside Design Guide as “The unobstructed, traversable area provided beyond the edge of the through traveled way for the recovery of errant vehicles” (27). This area includes shoulders, bike lanes, and auxiliary lanes, excepting those auxiliary lanes that function as through lanes (Figure 3n). Clear zone distances are most affected by traffic volume, speed, roadside slope, and curvature (27). In 2006, the Iowa Department of Transportation (Iowa DOT) initiated a program to mitigate RwD crashes, mainly focusing on the removal/relocation of hazards (e.g., trees, telephone poles, mailboxes) within the clear zone area and shielding or delineating objects, if achieving the first option was not feasible. The safety evaluation results showed that the number of total crashes dropped by up to 38 percent (6).

SUMMARY AND CONCLUSIONS
An investigation of 14 real-world case studies has provided an overview of current safety countermeasures practices for RwD crashes. These case study examples fall into three major categories: signs (i.e., chevrons, dynamic curve warning systems, and advance curve warning and advisory speed signs), pavement safety (high friction surface treatments, raised pavement markers, edge line pavement markings, safety edge, centerline rumble strips, and shoulder rumble strips), and roadside design (cable barrier, guardrail, breakaway supports for signs and lighting, clear zone improvements, and shoulder widening). The results of this study identify pavement safety as the most effective countermeasure for reducing total RwD-crash frequency and severity.

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REFERENCES
23. International Road Assessment Program (iRAP). iRAP Safety Assessment and Recommended Countermeasures.


