

TECHBRIEF



Safety Evaluation of Edge Line Rumble Stripes (ELRSs) on Rural, Two-Lane Horizontal Curves

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This document is a technical summary of the Federal Highway Administration report *Safety Evaluation of Edge Line Rumble Stripes (ELRSs) on Rural, Two-Lane Horizontal Curves* (FHWA-HRT-17-069).

Objective

The Federal Highway Administration (FHWA) established the Development of Crash Modification Factors (DCMF) program in 2012 to address highway safety research needs for evaluating new and innovative safety strategies (improvements) by developing reliable quantitative estimates of their effectiveness in reducing crashes. The goal of the DCMF program is to save lives by identifying new safety strategies that effectively reduce crashes and promote those strategies for nationwide implementation by providing measures of their safety effectiveness and benefit-cost (B/C) ratios through research. State transportation departments and other transportation agencies need to have objective measures for safety effectiveness and B/C ratios before investing in new strategies for statewide safety improvements. Forty State transportation departments provide technical feedback on safety improvements to the DCMF program and implement new safety improvements to facilitate evaluations. These States are members of the Evaluation of



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Low-Cost Safety Improvements Pooled Fund Study, which functions under the DCMF program.

This study evaluated the application of edge line rumble stripes (ELRSs) on rural, two-lane horizontal curves. This strategy was intended to reduce the frequency of run-off-road (ROR) crashes and nighttime crashes by alerting drivers that they are about to leave the traveled lane and by enhancing visibility of the edge line during nighttime and wet-weather conditions.

Several research studies have examined the use of shoulder rumble strips (SRSs); however, research into the performance of ELRSs is rare and has not been rigorously evaluated. Additionally, milled rumble strips are installed on roadway segments, consisting of both horizontal tangents and horizontal curves. Installations on only horizontal curves are uncommon and, therefore, safety effectiveness evaluations have not focused on their effectiveness on horizontal curves specifically. This research focused on the safety effectiveness of ELRSs on rural, two-lane horizontal curves, taken from rumble stripe installations that are not specific to horizontal curves.

Introduction

ELRSs are a variation of the common SRSs used to alert drowsy or distracted drivers when they leave the travel lane to the right. SRSs and ELRSs both target ROR crashes. Key distinctions between

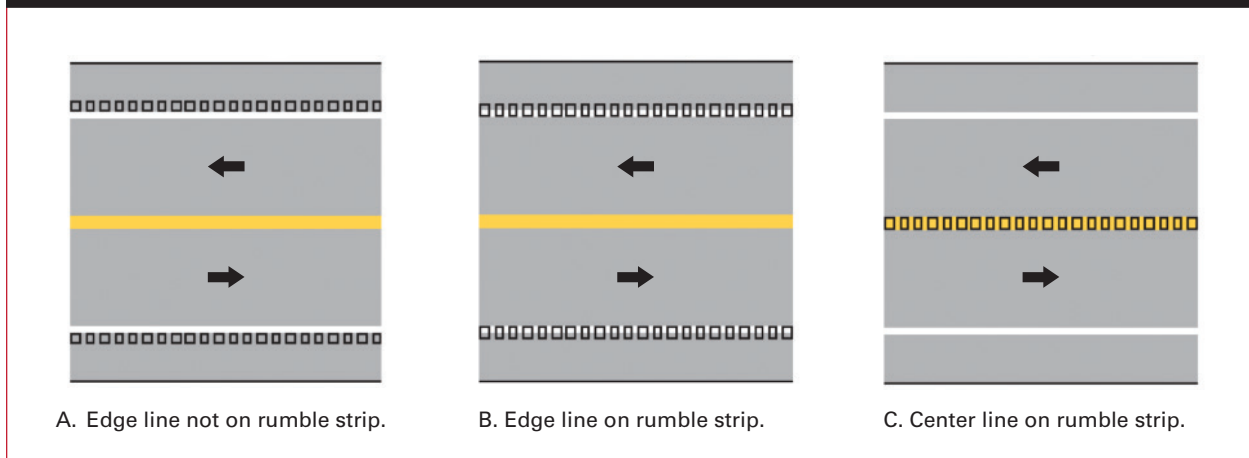
SRSs and ELRSs are provided in the following points:

- SRSs are provided on the shoulder between the pavement marking and the outside edge of the pavement and can be defined by their offset from the edge line pavement marking.
- ELRSs are installed where the edge line pavement marking would normally be placed, and the pavement marking is installed directly over the rumble strip. In this way, the rumble stripes are installed closer to the travel lane than common SRSs. Additionally, vertical faces are created within the milled rumble strip to which pavement markings are applied, thereby enhancing the visibility of the edge line during nighttime and wet-weather conditions.

The *Manual on Uniform Traffic Control Devices* (MUTCD) defines rumble strips as either slightly raised or depressed road surfaces with a rough texture designed to provide a haptic alert for inattentive drivers leaving the travel lane.⁽¹⁾ As shown in figure 1, rumble strips may be installed either on the shoulders or center line on rural, two-lane highways, and the edge line may be adjacent to the rumble strip or overlapping with it, creating a rumble stripe.

The literature review revealed that SRSs have been studied extensively on all facility types, including rural, two-lane highways. However, few

Figure 1. Illustrations. Examples of longitudinal rumble strip markings.⁽¹⁾



Note: Arrows indicate the direction of travel; hollow squares indicate rumble strip; edge line may be located alongside the rumble strip (A) or on the rumble strip (B); the center line markings may also be located on a center line rumble strip (C).

research studies considered the safety effectiveness of ELRSs, particularly the effectiveness on horizontal curves. Torbic et al., in the National Cooperative Highway Research Program (NCHRP) Report 641, evaluated the impact of SRS placement on safety, focusing on single-vehicle ROR (SVROR) fatal and injury crashes.⁽²⁾ The report defined placement as edge line and non-edge line, which it then compared to no rumble strips. The report defined ELRSs as rumble strips with an offset distance of 0 to 8 inches and non-ELRSs as having an offset of 9 inches or more. For two-lane rural roadways, there was no significant or practical difference between ELRSs and non-ELRSs. ELRSs were associated with a 33-percent reduction in SVROR fatal and injury crashes. Also, there is no evidence that suggests SRSs result in a reduction of SVROR crashes involving heavy vehicles.

Other researchers examined operational and visibility impacts of ELRSs. The

University Transportation Center for Alabama compared ELRSs to flat thermoplastic edge markings and found that the initial dry retroreflectivity was similar; however, ELRSs lost visibility at a lower rate due to cumulative traffic passes.⁽³⁾ ELRS wet retroreflectivity was higher than flat thermoplastic markings, but degradation could not be compared. The Mississippi Department of Transportation (MDOT) installed ELRSs on a portion of Interstate 59 with generally encouraging results.⁽⁴⁾ Preliminary data indicated that the strategy provided an excellent audible alert, increased visual awareness of the travel lane, increased reflectivity, and provided similar results as inverted profile striping, and Mississippi residents welcomed the installation. However, there were also concerns associated with the rumble stripes, including noise pollution and the potential for an increase in overcorrecting and head-on crashes.

Carlson et al. examined wet-night visibility of pavement markings using experimental drivers on a closed rain tunnel.^(5,6) The study tested nine different treatments in random orders and measured perception distance for each sample location. The driver alerted the researcher when he or she observed a marking and when the type could be determined. Part of this research included the testing of rumble stripes. The findings suggest there is little difference between flat thermoplastic lines and rumble stripe lines at low rainfall rates. However, the detection distance was 13 to 38 percent greater for rumble stripe lines for medium and heavy rainfall rates.

Methodology

This research examined the safety impacts of ELRSs on rural horizontal curves in Kentucky and Ohio. The objective was to estimate the safety effectiveness of this strategy as measured by crash frequency. Excluding intersection-related and animal crashes, the project team included the following crash types:

- Total (all types and severities combined).
- Fatal and injury (K, A, B, and C injuries on KABCO scale) (K is fatal injury, A is incapacitating injury, B is non-incapacitating injury, C is possible injury, and O is property damage only).
- ROR (all severities combined).
- Nighttime (including dusk and dawn; all severities combined).

- Nighttime ROR (including dusk and dawn; all severities combined).

A further objective was to conduct a disaggregate analysis to investigate whether the safety effects vary by factors such as the level of traffic volumes, the frequency of crashes before treatment, posted speed limit, and shoulder width.

The evaluation of overall effectiveness included the consideration of the installation costs and crash savings in terms of the B/C ratio.

The project team used the empirical Bayesian (EB) methodology for observational before–after studies for the evaluation.⁽⁷⁾ This methodology is considered rigorous in that it accounts for regression to the mean using a reference group of similar but untreated sites. In the process, the project team used safety performance functions (SPFs), and the use of these addresses the following:

- It overcomes the difficulties of using crash rates in normalizing for volume differences between the before and after periods.
- It accounts for time trends.
- It reduces the level of uncertainty in the estimates of safety effect.
- It properly accounts for differences in crash experience and reporting practice in amalgamating data and results from diverse jurisdictions.

The methodology also provides a foundation for developing guidelines for estimating the likely safety consequences of a contemplated strategy.

The project team estimated the SPFs used in the EB methodology through generalized linear modeling assuming a negative binomial error distribution, which is consistent with the state of research in developing these models. In specifying a negative binomial error structure, the project team estimated an overdispersion parameter, which they used in the EB calculations, iteratively from the model and the data. For a given dataset, smaller values of this parameter indicate relatively better models.

The full report includes a detailed explanation of the methodology, including a description of how the estimate of safety effects for target crashes was calculated.

Results

Due to differences in application in Kentucky and Ohio, the results are presented separately. The Kentucky results represent the safety effectiveness of only ELRS application, while the Ohio results include the effects of a simultaneous statewide sign upgrade program. In this program, many curves

received new or upgraded advance warning signs, in-curve warning signs, and updates to advisory speeds. The results are presented in two parts. The first part contains aggregate results, and the second part is based on a disaggregate analysis that attempted to discern factors that may be most favorable to the installation of ELRSs on rural, two-lane horizontal curves. The second part focuses on Ohio data, since the sample sizes are too small in Kentucky for further disaggregate analysis.

Aggregate Analysis

Table 1 provides the estimates of expected crashes in the after period without treatment, the observed crashes in the after period, and the estimated crash modification factor (CMF) and its standard error (SE) for all crash types considered in Kentucky. Table 2 presents the results for Ohio.

The results for Kentucky indicate statistically significant reductions for all crash types except for nighttime ROR crashes at the 95-percent confidence level. Nighttime crashes have the

Table1. Results for Kentucky.

Statistic	Total	Fatal and Injury	ROR	Nighttime	Nighttime ROR
EB estimate of crashes expected in the after period without strategy	113.9	40.8	67.6	33.1	22.5
Count of crashes observed in the after period	86	26	50	21	17
Estimate of CMF	0.75*	0.64*	0.74*	0.63*	0.75
SE of estimate of CMF	0.09	0.14	0.11	0.14	0.19

*Indicates statistically significant results at the 95-percent confidence level.

Table 2. Results for Ohio.

Statistic	Total	Fatal and Injury	ROR	Nighttime	Nighttime ROR
EB estimate of crashes expected in the after period without strategy	514.2	208.6	392.7	191.6	160.1
Count of crashes observed in the after period	405	165	305	144	114
Estimate of CMF	0.79*	0.79*	0.78*	0.75*	0.71*
SE of estimate of CMF	0.04	0.07	0.05	0.07	0.07

*Indicates statistically significant results at the 95-percent confidence level.

smallest CMF (which translates to the greatest reduction) with a CMF of 0.63. Total, fatal and injury, and ROR crashes have CMFs of 0.75, 0.64, and 0.74, respectively. The CMF for nighttime ROR crashes is consistent with other crash types; however, the sample size is very small. The CMFs are smaller than, but consistent with, those found in the most comprehensive and reliable study of SRSs to date, NCHRP Report 641.⁽²⁾ Based on a before–after EB analysis, the project team found that milled SRSs have a crash reduction of 16 percent (SE = 8) for all SVROR crashes and 36 percent (SE = 10) for SVROR fatal and injury crashes.⁽²⁾ However, the analysis results for SRSs in NCHRP Report 641 considered segments with both horizontal tangents and curves; therefore, a direct comparison of results cannot be made. It is also important to remember that all crash types considered in this research exclude intersection-related and animal crashes.

The results for Ohio indicate statistically significant reductions for all crash

types. Nighttime ROR crashes have the smallest CMF with a CMF of 0.71. Total, fatal and injury, ROR, and nighttime crashes have CMFs of 0.79, 0.79, 0.78, and 0.75, respectively. As with the Kentucky results, the CMFs are consistent with those found in NCHRP Report 641.⁽²⁾ The resulting Ohio installation CMFs reflect the installation of ELRSs on horizontal curves as well as the impact of the statewide signing program. Due to the spillover effects of the signing program, further analyses involving curves that specifically received new or additional signs were not fruitful. The results indicated that there is little to no additional benefit for the combination of ELRSs and horizontal curve signing in comparison to horizontal curve signing only.

Disaggregate Analysis of Ohio Data

The disaggregate analysis sought to identify those conditions under which the treatment is most effective. Since ROR, nighttime, and nighttime ROR crashes are the focus of this treatment,

these crash types are the focus of the disaggregate analysis. Additionally, disaggregate results are presented for total crashes and fatal and injury crashes. The data sample for Kentucky is too small to perform disaggregate analyses; therefore, disaggregate analyses focus on Ohio data.

The project team identified several variables as being of interest and available, including degree of curve, posted speed limit, paved shoulder width, lane width, annual average daily traffic (AADT), and before-period expected crash frequency. Disaggregate results are provided by AADT in table 3 and before-period expected crash frequency in table 4. The number of crashes in the after period is presented for each CMF to indicate the sample size available. Several of the estimated CMFs rely on small samples, especially for nighttime crashes and nighttime ROR crashes.

As shown in table 3, smaller CMFs (i.e., larger safety benefits) were found for all crash types for sites with an AADT of 4,000 or more vehicles per day;

however, the 95-percent confidence intervals overlap for each crash type. At AADTs lower than 4,000 vehicles per day, for example, an ROR CMF of 0.82 was estimated versus a CMF estimate of 0.64 for AADTs of 4,000 or greater vehicles per day. A similar difference was found for all other crash types. The 4,000 vehicles per day AADT cutoff is consistent with previous research by Patel et al. and Lyon et al.^(8,9)

The 95-percent confidence intervals did not overlap for total crashes and ROR crashes. Due to the differences in the frequencies of different crash types, the before-period expected crash frequency cutoff varied for each crash type. For example, an ROR CMF of 1.13 was estimated for horizontal curves with an ROR before-period expected crash frequency less than 0.20 crashes per year. This can be compared to a CMF of 0.66 for horizontal curves with 0.20 or more before-period expected crashes per year. Note that the CMF of 1.13 for an ROR before-period expected crash rate less than 0.20 was not statistically significant. Similar results were found for all other crash types.

Table 3. Ohio results by AADT.

Crash Type	<4,000 Observed Crashes	<4,000 CMFs (SE)	4,000+ Observed Crashes	4,000+ CMFs (SE)
Total	289	0.82* (0.06)	116	0.72* (0.08)
Fatal and injury	118	0.82* (0.08)	47	0.72* (0.12)
ROR	239	0.82* (0.06)	66	0.64* (0.09)
Nighttime	105	0.79* (0.08)	39	0.66* (0.12)
Nighttime ROR	88	0.78* (0.09)	26	0.54* (0.11)

*Indicates statistically significant results at the 95-percent confidence level.

Table 4. Ohio results by before-period expected crash frequency.

Crash Type	Value	Less Than Value Observed Crashes	Less Than Value CMFs (SE)	Greater Than or Equal to Value Observed Crashes	Greater Than or Equal to Value CMFs (SE)
Total	0.25	136	1.09 (0.11)	269	0.69* (0.05)
Fatal and injury	0.10	63	1.00 (0.14)	102	0.70* (0.08)
ROR	0.20	111	1.13 (0.12)	194	0.66* (0.05)
Nighttime	0.15	85	0.93 (0.11)	59	0.59* (0.08)
Nighttime ROR	0.075	38	0.85 (0.15)	76	0.66* (0.08)

*Indicates statistically significant results at the 95-percent confidence level.

Caution should be used in interpreting and applying these disaggregate CMF results because of correlation among variables and because they were not robust enough to develop crash modification functions. A crash modification function is a formula used to compute the CMF for a specific site as a function of its site-specific characteristics. For example, crash modification functions would allow the estimation of CMFs for different levels of AADT and before-period crash frequency. Additionally, the disaggregate analysis results used the EB analysis data, which includes the effects of the statewide horizontal curve signing program. However, the disaggregate analysis CMFs may be used in prioritizing treatment sites. For example, sites with a high proportion of ROR crashes and high AADTs will have high priority.

Economic Analysis

The research team conducted an economic analysis to estimate the B/C

ratio for this strategy on rural, two-lane horizontal curves. For the purposes of the economic analysis, the assumed treatment is the application of ELRSs. The team used the recommended CMFs of 0.75 for Kentucky and 0.79 for Ohio to estimate the benefit of this treatment strategy. The Ohio results likely include the impact of additional sign upgrades, for which the Ohio Department of Transportation (ODOT) did not have data that could be included in this analysis. Additionally, the project team did not include the cost of pavement markings in the study because they are already present on the roadway, and the ELRSs did not affect the lifespan of edge line pavement markings. Treatment costs range from \$1,700 per mile for Ohio and \$2,500 per mile for Kentucky. Service life is 12 to 15 years for Kentucky and 7 to 10 years for Ohio (ODOT noted that the service life lasts as long as the pavement). The project team assumed a conservative value of 12 years for Kentucky and 7 years for Ohio.

The FHWA Office of Safety R&D suggests that the Office of Management and Budget *Circular A-4* be used to determine the conservative real discount rate of 7 percent.⁽¹⁰⁾ The project team applied this discount rate to calculate the annual cost of the treatment for 12-year and 7-year service lives in Kentucky and Ohio, respectively. With this information, the project team computed the capital recovery factor to be 7.94 for a 12-year service life and 5.39 for a 7-year service life.

The FHWA's most recent mean comprehensive crash costs, which are disaggregated by crash severity, location type, and speed limit, are based on 2001 dollar values.⁽¹¹⁾ The 2001 unit costs for property-damage-only (PDO) and injury crashes from the FHWA report (\$7,428 and \$158,177) were multiplied by the ratio of the 2014 (when the analysis was performed) value of a statistical life of \$9.2 million to the 2001 value of \$3.8 million.^(12,13) By applying this ratio of 2.42 to the unit costs for PDO and injury crashes and then weighting by the frequencies of these two crash types in the after period, the project team obtained the aggregate 2014 unit costs for total crashes of \$128,268 and \$166,603 for Kentucky and Ohio, respectively.

The project team calculated the total crash reduction by subtracting the actual crashes in the after period from the expected crashes in the after period had the treatment not been implemented. The number of crashes saved

per mile-year is 0.812 in Kentucky and 0.913 in Ohio. The project team obtained these numbers by dividing the total crash reduction by the number of after-period mile-years per site.

The annual benefit (i.e., crash savings) of \$104,165 in Kentucky and \$150,368 in Ohio is the product of the crash reduction per mile-year and the aggregate cost of a crash (all severities combined). The B/C ratio is calculated as the ratio of the annual benefit per mile to the annual cost per mile. The project team estimates the B/C ratio to be 331:1 in Kentucky and 477:1 in Ohio. USDOT recommended a sensitivity analysis be conducted by assuming values of a statistical life of 0.57 and 1.41 times the recommended 2014 value.⁽¹²⁾ These factors were applied directly to the estimate B/C ratios to obtain a range of 189:1 to 467:1 for Kentucky and 272:1 to 672:1 for Ohio. On first inspection, the B/C ratios are larger than expected for an installation of this type. However, the installations took place on corridors, while the analysis only looked at the safety effects on horizontal curves. Horizontal curves have higher crash rates than overall corridors, and the cost per mile of installation would not be representative for installations only on horizontal curves. As a curve-specific treatment, the B/C ratio would likely be reduced due to the higher deployment cost for spot-specific installations; however, these results suggest that the treatment can be highly cost effective.

Summary and Conclusions

The objective of this study was to undertake a rigorous before–after evaluation of the safety effectiveness, as measured by crash frequency, of ELRSs applied on rural, two-lane horizontal curves. The CMFs shown in table 5 and table 6 are recommended for the various crash types. The results for Kentucky are based on smaller sample sizes, and the results for Ohio include the effects of a statewide horizontal curve warning sign upgrade program.

To date, the most comprehensive and reliable study of SRSs is published in NCHRP Report 641—*Guidance for the Design and Application of Shoulder and Centerline Rumble Strips*.⁽²⁾ Compared to the results of that study for ELRSs, the results suggest that placing rumble strips on or near the edge line for

horizontal curves, specifically, may result in greater reductions in all crash types. It also appears that ELRSs are associated with significant reductions in nighttime crashes but do not further reduce nighttime ROR crashes on horizontal curves.

A disaggregate analysis of the results indicated that, for horizontal curves with AADTs greater than 4,000 for all crash types, there are larger safety benefits; however, the differences by AADT are not statistically significant at the 95-percent confidence level. The disaggregate analysis further indicated larger safety benefits for horizontal curves with a higher before-period expected crash frequency. The results suggested no benefit for curves with low before-period expected crash frequencies for all crash types. The difference in CMFs between low before-period expected crash frequency and

Table 5. Recommended CMFs for ELRSs based on Kentucky data.

Statistic	Total	Fatal and Injury	ROR	Nighttime	Nighttime ROR
Estimate of CMF	0.75*	0.64*	0.74*	0.63*	0.75
SE of estimate of CMF	0.09	0.14	0.11	0.14	0.19

*Indicates statistically significant results at the 95-percent confidence level.

Table 6. Recommended CMFs for ELRSs and curve signage based on Ohio data.

Statistic	Total	Fatal and Injury	ROR	Nighttime	Nighttime ROR
Estimate of CMF	0.79*	0.79*	0.78*	0.75*	0.71*
SE of estimate of CMF	0.04	0.07	0.05	0.07	0.07

*Indicates statistically significant results at the 95-percent confidence level.

high before-period expected crash frequency is statistically significant for total and ROR crashes.

The project team estimated the B/C ratios to range from 189:1 to 467:1 for Kentucky and from 272:1 to 672:1 for Ohio. The high B/C ratios should be considered in the context that the installations took place on corridors, while the analysis only looked at the safety effects on horizontal curves. Horizontal curves have higher crash rates than overall corridors, and the cost per mile of installation would not be representative for installations only on horizontal curves. Additionally, the safety effectiveness evaluation in Ohio included the impacts of upgraded horizontal curve warning signage. As a curve-specific treatment, the B/C ratio would likely be reduced due to the higher deployment cost for spot-specific installations; however, these results suggest that the treatment—even its most expensive variation—can be highly cost effective.

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