

An Evaluation of the Effectiveness of Wider Edge Line Pavement Markings



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1.0 Introduction

Fatalities on America's rural roadways have decreased in recent years, but remain at unacceptably high levels. Despite only making up 23 percent of the US mileage, fatalities on rural two-lane highways made up 57 percent of all traffic fatalities in 2009—resulting in more than \$77 billion in losses for that year alone. Moreover, a rural motorist is 2.7 times more likely to be involved in a fatal crash per mile traveled than their urban counterpart.

While progress has been made and fatalities have declined 22.5 percent since 2000, more can and should be done to further drive down rural fatal crashes. State DOTs have a variety of potential policy options at their disposal: installing signs and rumble strips, widening road stripes, and other less commonly used methods. Gradually, state DOTs have increased the use of wider edge lines, despite an inability to provide quantitative evidence of decreases in crashes.

Over the past decade, researchers have found that edge lines can improve vehicle operations, but direct statistical evidence showing improvements in safety have proven difficult to obtain. Recent research from the Federal Highway Administration overcame this hurdle with a recent study analyzing a large amount of data from three states using three separate rigorous statistical measures (Carlson et. al., 2012). This study provides strong evidence that wider edge lines are a cost effective, statistically sound approach to reducing a crashes and fatalities on two-lane rural highways.

This paper will review the literature surrounding wider edge lines, including describing wider line functionality, safety impacts, and detailing state practices. It will provide a comparative cost-benefit analysis of wider lines and other common improvements to determine the most cost effective method for reducing fatalities. Finally, it will recommend strategies for state DOTs to increase safety, and suggest a need to revise the MUTCD definitions on marking widths.

2.0 Understanding Edge Lines

To the untrained eye, a road with wider edge lines might go unnoticed. In fact, it would be hard to fault the average driver for not noticing. A road with typical wider edge lines will only increase the standard four-inch line width by two inches (i.e., from four inches to six inches). This relatively small change on a roadway can, however, have a very large impact on driver safety. To understand these impacts, it is best to first discuss how edge lines function and what value they add.

Edge lines and all longitudinal pavement markings provide a valuable continuous stream of information about the roadway that signs or signals cannot supply. They alert the driver to changes in the roadway and help the driver maintain their position inside of the lane without requiring the driver to take their eyes off of the road. They separate opposing traffic streams and channel traffic into the proper roadway positions.

A long history of research dating back to 1957 confirms the safety value of edge lines. Table 1 summarizes the findings of several studies that analyzed crash reductions as a result of installing edge lines. While each study’s exact circumstances, methodology, and results vary—all studies consistently found the existence of edge lines improved roadway safety.

Table 1: Crash Reductions Resulting from the Installation of Edge Lines

Author	Year	Location	Result
Musick	1957	Ohio	<ul style="list-style-type: none"> • 19% reduction in crashes • 37% reduction in fatalities and injuries • 35% decrease in nighttime crashes
Basile	1959	Kansas	<ul style="list-style-type: none"> • 78% reduction in fatalities • Significant reduction in intersection crashes during both daytime and night
Tsyganov	2005	Texas	<ul style="list-style-type: none"> • 26% reduction in crashes

While the safety benefit of using edge lines is clear, policy decisions require a comprehensive understanding of all factors, including financial constraints. A unique study analyzed the benefits and costs of implementing edge lines under various roadway situations (Miller, 1991). The analysis found that, on average, the installation of pavement stripes resulted in a 60:1 benefit/cost ratio with average annual benefits estimated at \$19,226 per line-mile. Edge lines’ low installation costs and large safety benefits result in a strong return for each taxpayer’s dollar.

2.1 Edge Lines’ Effect on Vehicle Operation

While the preceding research shows consistent reductions in crashes following the installation of edge lines, other research methods have had less clear results. Often researchers will develop alternative methods of studying the impacts of a process due to logistical constraints or to gain a more thorough understanding of why a change occurred. Researchers analyzed how a motorist will change their driving behaviors in the presence of edge lines. The indirect measures are correlated with crash rates, so improving driver performance in these areas would help both predict crash reductions and provide an explanation of why the reductions may occur.

Surprisingly, these indirect measures often found that the presence of edge lines has inconsistent results on vehicle operation. A meta-analysis of how vehicle speed change in the presence of edge lines found that average vehicle speed changes ranged from -3 mph to +8.1 mph (Van Driel, Davidse, & van Maarseveen, 2004). Two additional studies concluded that edge lines do not improve vehicle speed under varying conditions (Donnel, Lee, Molino, & Opiela, 2007; Sun & Tekell, 2005).

Researchers also analyzed how edge lines impact vehicle lateral lane position. Lateral lane positioning is the ability of a motorist to maintain an appropriate position inside the lane lines. A meta-analysis found widely varying effects, including a range of results from 10.5 inch shift toward the centerline to a 14 inch shift away (Van Driel, Davidse, & van Maarseveen, 2004). These disparate results led the researchers to conclude that the net effect was essentially zero.

Another study found that edge lines helped drivers travel in a more centralized and uniform path (Sun & Tekell, 2005). Still another study found positive results and concluded that edge lines were beneficial for vehicle operation (Tsyganov, Machemehl, & Warrenchuk, 2005).

Overall, standard edge lines have a beneficial impact to driver safety. Consistent results show that the presence of edge lines can reduce a variety of crash statistics. Studies analyzing vehicle operation have found less consistent results, although some do show improvements.

3.0 The Case for Wider Edge Lines

The preceding studies led researchers and organizations to the following logical conclusion: if the presence of a four-inch edge line can create a dramatic improvement in safety measures, then perhaps a wider edge line with greater visibility could improve safety by an additional margin. Despite the presence of logistical hurdles, researchers attempted to find evidence supporting or refuting their hypothesis.

For some time, the research floundered with inconsistent and statistically insignificant results. Nonetheless, states steadily increased the usage of wider edge lines—backed by support from motorists who consistently indicate a preference for wider edge lines and various studies showing positive (though indirect) evidence. This frustrating lack of a consistent and clear impact to safety changed with the recent completion of a study demonstrating that the use of wider edge lines results in statistically significant, consistent, and clear impacts to driver safety.

As a brief clarification, “wider edge lines” refers to any increase in marking width over the minimum four-inch standard set out by the MUTCD. This should not be confused with “wide lines” as defined by the MUTCD, which is any line at least twice the minimum width.

3.1 Indirect Measures

Researchers approached the question of analyzing wider lines in two ways: first, they used indirect measures like driver opinions, vehicle operations, and visibility; and second, they attempted to analyze directly how wider lines would reduce a variety of crash statistics. Researchers often used the indirect measures as a surrogate measure for safety—positive results would imply that roadway safety had improved. Overall, the indirect measures found mixed, although often positive results for the various measures. These findings provide some legitimacy and evidence to support the need for wider edge lines.

3.1.1 Opinion Surveys

A variety of opinion polls and studies have shown that motorists value the use of wider edge lines. A 1997 public opinion poll from South Dakota found that motorists and legislators ranked “keeping stripes visible” third-highest out of 21 possible attributes for resource allocation (Huberty & Swenson, 1997). A follow up survey found that 81 percent of respondents felt that

poor pavement markings would “somewhat interfere” or “very likely interfere” with safe travel (Bender & Schamber, 2000).

Another study found that drivers participating in a field detection distance evaluation judged wider markings as more favorable than four-inch markings (Ohme, 2001). Hostetter, et al observed similar results in a driving simulator evaluation of eight-inch and four-inch edge lines (Pietrucha, Hostetter, Staplin, & Obermeyer, 1996). Still another study had 18 American Association of Retired Persons (AARP) driving instructors drive a test course during daytime and nighttime. 94 percent of respondents reported that eight-inch edge lines affected the way they drove, and that wider markings aided their ability to stay in their lane (Ward, 1985).

3.1.2 Vehicle Operations

When motorists drive a vehicle, they respond to the environment in which they are placed. Driving on a road without adequate visibility or under other negative conditions will likely yield more crashes than driving under optimal conditions. When one makes a relatively marginal change to an environment (like adding a few inches of width to road stripes), motorists will respond, but the minor nature of the changes and the relative infrequency with which crashes occur may require a large amount of data to detect a difference.

As a result, researchers analyzed how motorists operate vehicles differently on roads with wider striping to understand how these changes would impact safety. A study in Virginia found that average lateral vehicle placement was significantly more centered on an eight-inch road vs. a four-inch road (Cottrell, 1985). The differences in other driver performance measures were not statistically significant.

Another study observed fewer lane departures on curved highway segments with eight-inch edge lines when compared to four-inch edge lines (Hughes, McGee, Hussain, & Keegel, 1989). The authors commented that driver performance when traversing roads with an eight-inch edge line were better than with a four-inch edge line. Finally, a simulation study found that wider edge lines have a large positive effect on a motorist’s ability to lane keep under low contrast situations, similar to those on wet roads (McKnight, McKnight, & Tippetts, 1998).

3.1.3 Visibility Studies

When motorists operate a vehicle they use pavement markings to guide them through the roadway. More visible pavement markings can increase the distance with which the lines are detectable and may improve a motorists’ ability to perceive the marking in their peripheral vision. These improvements may improve lane keeping and positively impact safety. Researchers have performed multiple studies to test this hypothesis.

A first study found that increasing pavement markings to eight inches from four inches provides a statistically significant increase in average detection distances for young drivers on a left curve (Zwahlen & Schnell, 1995). They also found that retroreflectivity (or the amount of light

returned from a source) was substantially higher than traditional markings. Another study found that six-inch markings have a statistically significant improvement over four-inch markings for end-detection distances among both older and younger drivers under dry conditions at night (Ohme, 2001). A simulator study found that eight-inch markings provide a marginal improvement over four-inch markings for both older and younger drivers at low levels of marking brightness (Pietrucha, Hostetter, Staplin, & Obermeyer, 1996).

Another study found that increasing markings from four inches to six inches resulted in an increase in detection distance, but there was no increase in detection distance when increasing width from six inches to eight (Gibbons, McElheny, & Edwards, 2006). A recent study comparing various four-inch and six-inch markings under wet and dry conditions found that two of the tested markings produce marginal improvements in detection distances under wet conditions (Carlson, Miles, Pike, & Park, 2007). They also found that two of the six-inch and two of the four-inch markings improved detection distances under dry conditions.

A recently completed eye-tracking study provides evidence suggesting that increasing edge line width from four to six to eight inches along horizontal curves provides a more comfortable driving environment for drivers and provides more time for drivers to focus on critical driving tasks (Miles, Carlson, Eurek, Re & Park, 2010). The same study also determined that brighter pavement markings did not impact driver eye-looking patterns. Combined, these findings suggest that increasing the width of pavement markings may be more valuable than increasing their retroreflective performance—at least above a particular threshold that may be adequate.

3.2 Direct Measures

The most direct way to assess how wider edge lines impact safety is to measure reductions in crashes. Most studies have had difficulty finding statistically significant changes in crash figures for several reasons. First, a finding of statistical significance requires a large amount of time, resources, and site control—all of which are often difficult to attain for researchers and agencies that commonly carry out such studies. Second, measuring change in a dependent variable like crashes can be quite difficult due to its infrequent and erratic nature. Finally, measuring the change in an infrequent and erratic dependent variable is made more difficult when the change in the independent variable is subtle, as is the case with wider edge lines. This also requires a very large amount of data before researchers can attribute any difference to the road striping.

Table 2 below details the results a several studies that analyzed the impact from increasing the width of pavement markings on crash safety (note: not all studies looked specifically at edge lines). As the table shows, researchers have largely struggled to find clear and consistent safety increases from increasing marking width. These struggles likely resulted from the statistical hurdles described above. A few of the studies however, did show statistical significance, as was the case with the Missouri and Hughes studies. As a note, the state DOT studies are unpublished internal reports.

Table 2: Results of Increasing Pavement Marking Width on Crashes

Author	Year	Methodology	Result
Hall	1987	Compared 8" to 4"	<ul style="list-style-type: none"> No statistically significant difference in run-off-road (ROR) crash reductions
Cottrell	1985	Compared 8" to 4"	<ul style="list-style-type: none"> No statistically significant difference in ROR crash reductions
Hughes	1989	Compared 8" to 4" on two-lane rural roadways	<ul style="list-style-type: none"> No reduction in crash frequency on roads with between 5,000 and 10,000 vehicles per day Decrease in total crash rate, total crash frequency, and injury/fatal crash rate for 24-foot-wide rural roads with average daily traffic (ADT) volumes between 2,000 and 5,000 and 8" stripes
MD DOT		10" markings installed on two hazardous roadways	<ul style="list-style-type: none"> No conclusive results
KS DOT		Before and after comparison of 8" to 4" on two-lane highway without shoulders	<ul style="list-style-type: none"> No appreciable difference between before and after periods
ME DOT		Compared 6 and 8" to 4"	<ul style="list-style-type: none"> No significant ROR crash reduction
TX DOT		Before and after comparison of rural highways with 8" to 4"	<ul style="list-style-type: none"> No significant ROR crash reduction
MO DOT		Compared 4" to 6"	<ul style="list-style-type: none"> 13.7% reduction in fatal and disabling injury crashes, and 6.4% reduction in fatal and all injury crashes on roads that received 6" lines and resurfacing 44.9% reduction in fatal and disabling injury crashes, and 24.4% reduction in fatal and all injury crashes on roads that received 6" lines without resurfacing

Despite consistently inconclusive results, the research continued—undeterred by logistical hurdles and determined to find a clear result. A recent study performed at the Texas Transportation Institute (TTI) has transformed the discussion by finding clear and consistent results through rigorous analytical methods. This recent study analyzed a large amount of data from Michigan, Kansas, and Illinois to identify how wider edge lines impact several crash types. The study utilized three different statistical methodologies due to logistical constraints presented from the data.

After analyzing the data, the researchers found “detailed evidence to suggest that wider edge lines are effective in reducing crashes on rural, two-lane highways, especially with regard to relevant target crashes such as single vehicle crashes and related disaggregate crashes (e.g. single vehicle night, single vehicle fatal injury)” (Park, Carlson, Porter, & Andersen, 2012, p. 19). According to the authors, this study was the first that analyzed “extensive crash data from multiple states and [used] advanced statistical methods to assess the safety effects of wider lines”. All three of the analyses yielded consistently positive, statistically significant results.

Table 3 (reproduced from the original report) details the results of the analyses. As a reference, bolded entries are findings with statistical significance. PDO crashes are crashes involving property damage only. Finally, the researchers utilized two separate analytical methods on the

data from both Kansas and Michigan. The second analytical method placed tighter controls to ensure rigor in the face of logistical constraints. As a result, the second analytical method includes more conservative measures.

Table 3: Percent Crash Reduction Estimates for Wider Edge Lines on Rural Two-Lane Highways Based on the Crash Data from Three States (Park 2012)

Crash Type	Percent Crash Reduction				
	KS (Analysis 1)	KS (Analysis 2)	MI (Analysis 1)	MI (Analysis 2)	IL (Without animal collisions)
Total	17.5	15.0	27.4	19.4	30.1
Fatal and Injury	36.5	24.4	15.4	16.1	37.7
PDO	12.3	8.6	30.5	19.6	23.9
Day	28.6	18.6	20.3	12.0	29.1
Night	3.7	-2.4	30.7	18.8	29.9
Daytime Fatal and Injury	41.5	22.7	8.2	23.0	36.0
Nighttime Fatal and Injury	12.7	5.8	22.6	-5.8	34.2
Wet	22.9	17.2	67.2	62.6	34.7
Wet Night	24.3	24.9	76.9	79.2	35.7
Single Vehicle	27.0	28.7	30.0	18.7	37.0
Single Vehicle Wet			73.8	65.9	32.8
Single Vehicle Night	18.4	14.1	29.4	18.0	29.5
Single Vehicle Fatal and Injury	36.8	30.5	10.0	-1.9	42.2
Single Vehicle Night Fatal Injury	18.7	20.3	9.7		36.3
Older Driver					24.1
Fixed Object	19.0	22.4			29.5

As the table shows, the analyses found consistently positive, statistically significant changes for a variety of crash types. The study affirms the suspicions of state transportation agencies and researchers that, for a variety of reasons, could not find empirical evidence to support: wider edge lines can reduce crashes. This study provides transportation agencies with strong reasons to use wider edge lines on two-lane rural highways.

It is also worth noting that a separate analysis on the same study specifically analyzed the impact of wider edge on a variety of crash types on Michigan freeways and found “no consistent or statistically significant safety effect” (Carlson, et al., 2010, p. 209). This finding lends evidence to the hypothesis that wider edge lines are useful tools for crash prevention on two-lane rural highways, but may be ineffective for freeway applications.

4.0 Current State Practices

States have increased the usage of wider pavement markings in recent years, despite the absence of strong quantitative evidence of their safety benefits. Two previous studies analyzed who, what, where, and why states use wider pavement markings by distributing questionnaires to state transportation agencies (Gates & Hawkins, 2002) (Obeng-Boampong, Pike, Miles, & Carlson,

2009). The studies were completed in 2001 and 2006, with the goal of tracking wider pavement marking usage over time.

4.1 Initial Study

The initial study found that 29 of 50 (58 percent) of states used wider edge markings to some degree for centerlines, edge line, and/or lane lines (Gates & Hawkins, 2002). State agencies most frequently (57 percent) cited improving visibility as the reason for using wider markings. The most significant finding of the initial study was that 85 percent (22 of 26) of the states east of the Mississippi River used wider markings, whereas only 29 percent (7 of 24) of the states west of the Mississippi River used wider markings. The researchers speculated that this may be due to states in the Atlantic Coastal area being the first to take up the practice, and that decision influencing neighboring states to do the same.

The initial study also found that 4 percent of states used wider edge lines only; 10 percent used wider lane lines only; 40 percent used wider centerline, lane lines, and edge lines; and 4 percent used a variety of practices (40 percent did not use wider lines at all). 42 percent of states used 4-inch lines only, 10 percent used 5-inch lines, 34 percent used 6-inch lines, 8 percent used 8-inch lines, and 6 percent of states used wider lines at multiple widths.

4.2 Follow-Up Study

The follow-up study did not achieve a 100 percent response rate, but among the states that did respond, 76 percent (22 of 29) used wider pavement markings to some degree (Obeng-Boampong, Pike, Miles, & Carlson, 2009). Five additional states reported using wider markings since the first study, and only one state (Oregon) ceased using wider markings since the first study.

States listed a variety of reasons for installing wider markings, none of which were predominate. A few of the more frequently cited reasons include a shift in state policy (20 percent), experimental purposes (16 percent), recommendations from other states (13 percent), and for high crash areas (11 percent). 24 percent of states reported using 4-inch lines only, 4 percent used 5-inch lines, 48 percent used 6-inch lines, 10 percent used 8-inch lines, and 14 percent of states used wider lines at multiple widths.

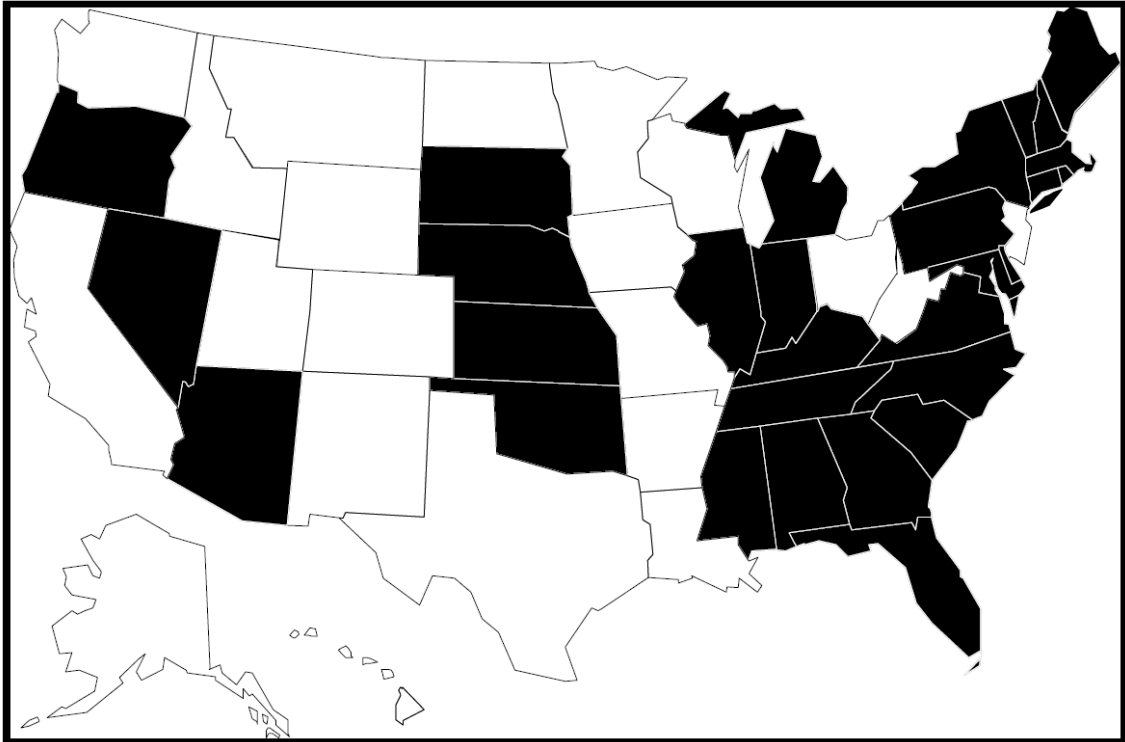


Figure 1: Use of Wider Markings among State DOTs (Black fill denotes use; Gates 2002)

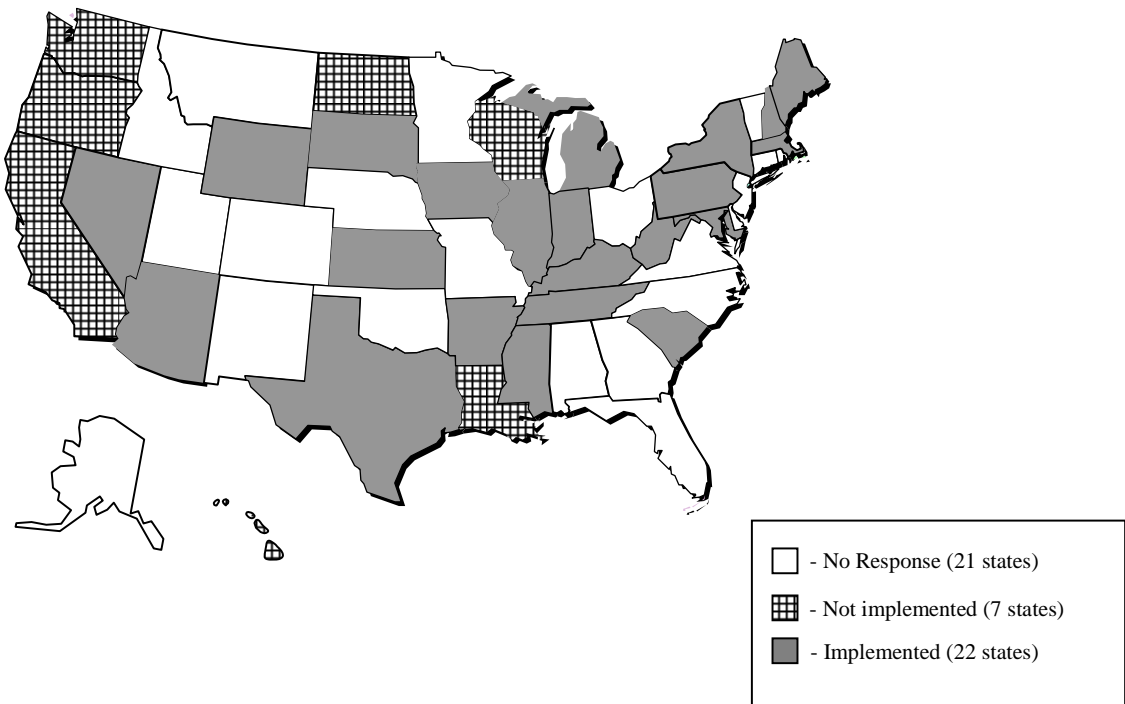


Figure 2: Use of Wider Markings among State DOTs (Obeng-Boampong 2009)

The follow-up study also asked states that did not use wider markings why they chose to not do so. The states reported four reasons:

- “Budget limitations;
- Need for published research or study on safety-benefits of wider markings;
- Currently improving striping procedures... and
- Higher priority on supplementing centerline markings with raised pavement markers” (p. 11).

After considering this list, at least three of the four concerns can be addressed through analyzing the current research. The recent TTI study addressed the need for research on the safety benefits by finding that wider edge lines consistently result in reductions in crashes. The first concern and final concern deal with budgets and priorities for safety, both of which are valid considerations. Every state has budgetary constraints and must make decisions about which policies provide the greatest benefit at the least cost. To help states evaluate the decision for wider edge lines, the following section will provide a cost-benefit analysis for wider edge lines, and compare the safety and monetary benefits to those of alternative strategies.

5.0 Comparative Cost-Benefit Analysis

Policy decisions do not take place in a vacuum, but within the context of political and economic constraints. In an era of decreased governmental revenues and increased austerity, policy makers are often concerned with making government more efficient and effective. These concerns can be assuaged by carefully considering the costs and benefits of policy options and selecting the most cost-effective policy.

5.1 Wider Edge Lines

Wider edge lines provide a variety of safety benefits, but researchers have not effectively estimated these costs and benefits. To better arm policy makers with more robust information, this analysis developed an original cost-benefit analysis on recent data.

5.1.1 Methodology

To develop a benefit-cost analysis of implementing wider edge lines on rural, two-lane highways, we utilized crash data from Kansas from the TTI study, “Safety Effects of Wider Edge Lines on Rural, Two-Lane Roads” (Park, Carlson, Porter, & Andersen, 2012). The financial focus of benefit-cost analysis resulted in a focus on the costs associated with fatal and injury crashes, since they are more reliable than PDOs and have established monetary thresholds.

The analysis described herein is based on the benefits and costs of fatal and injury crashes from the Kansas data set (shown in Table 3). The study of the Kansas data included two separate analytical methods, the second method provides a more conservative estimate of crash reductions.

To calculate the benefits and costs, we used the basic formula of summing the benefits from wider edge lines, discounting them over an assumed service life of edge lines (2 years assuming waterborne paint using a seven percent rate (per the standard set out by the Office of Management and Budget), and dividing the discounted benefits by the installation costs (Office of Management and Budget, 1992). We then divided the benefits by two to derive an average benefit per year, since the original benefits were aggregated over a two year time period.

Benefits for fatal and injury crashes were computed as the difference between estimated crashes and observed crashes, multiplied by the cost of the averted fatalities and injuries. In short, the monetary benefit of wider edge lines is equal to the savings from individuals not losing their lives and not being involved in an injury crash.

The analysis uses crash cost estimates from a National Highway Traffic Safety Administration (NHTSA) study, specifically tasked with developing cost estimates for various crash types, as well as the costs for minor injury crashes (MIC) and disabling injury crashes (DIC) from a recent Missouri Department of Transportation (MODOT) study (Blincoe, et al., 2002; Potts, Harwood, Bokenkroger, & Knoshaug, 2011). The MODOT found that DICs account for 22 percent of all injury crashes, and MICs account for 78 percent of all injury crashes. The costs were updated to 2011 dollars using the Consumer Price Index’s Inflation Calculator (Bureau of Labor Statistics, 2011). Table 4 below includes the costs for each crash type.

Table 4: Costs by Crash Type

Crash Type	Cost (Expressed in 2011 Dollars)
Fatal	\$4,422,636.22
Disabling injury	\$316,351
Minor injury	\$80,353

For this analysis, edge line installation costs were derived from a recent study at the Center of Transportation and Research Education (CTRE) at Iowa State University (Hawkins, N., Smadi, O., & Aldemir-Bektas, 2011). The cost for installing six inch waterborne edge lines is about \$0.15 per foot of marking. The cost of installing four inch waterborne edge lines is about \$0.10 per foot. The resulting difference in cost is \$528 per mile.

5.1.2 Results

The analysis resulted in a strong benefit to cost ratio for fatal crashes for both the first and second (more conservative) analytical methods. As Table 5 shows, the first method resulted in a ratio of \$43.96 in benefits for every \$1 invested. The second method resulted in a ratio of \$21.72 for every \$1 invested. These ratios are consistent, although smaller than those found in a previous study that found an ROI of \$117.6 for every \$1 invested in wider markings and resurfacing of urban two-lane highways (Potts, Harwood, Bokenkroger, & Knoshaug, 2011). The difference in ROI is likely due to the higher traffic volume on urban highways, which may result in higher total crash counts and a greater savings for the total reduction in crashes.

Table 5: Fatal Crash Costs and Benefits

	Analytical Method 1	Analytical Method 2
Estimated number of fatal crashes	10.22	16.76
Cost of estimated crashes	\$45,199,342	\$74,123,383
Observed number of fatal crashes	5.5	14
Cost of observed crashes	\$24,324,499	\$61,916,907
Fatal crashes averted	4.72	2.76
Savings from averted crashes	\$20,874,843	\$12,206,476
Total costs	\$858,528	\$1,016,189
Benefit to cost ratio	\$43.96 : \$1	\$21.72 : \$1

The analysis of injury crashes resulted in a weaker, but still strong benefit to cost ratio for both of the analytical methods considered. As Table 6 shows, every \$1 invested in wider edge lines results in \$11.16–\$11.24 returned in reduced injury crashes and their associated costs.

Table 6: Injury Crash Costs and Benefits

	Analytical Method 1	Analytical Method 2
Estimated number of injury crashes	112.84	189.4
Cost of estimated crashes	\$14,924,874	\$25,053,084
Observed number of injury crashes	72.5	142
Cost of observed crashes	\$9,589,761	\$18,782,704
Injury crashes averted	40.335	47.41
Savings from averted crashes	\$5,335,214	\$6,270,381
Total costs	\$858,528	\$1,016,189
Benefit to cost ratio	\$11.24 : \$1	\$11.16 : \$1

The results were separated to illustrate the impact from either policy choice in isolation; however the benefits are actually cumulative. Stated differently, the benefit that occurred in Table 6 can be added to the benefit from Tables 5 without double counting the costs or benefits. This method results in an overall benefit to cost ratio for the first and second methods of \$55.20 and \$32.87 returned for every \$1 invested, respectively.

5.2 Rumble Strips

The results of this paper demonstrated that wider edge lines can be an effective way to reduce crashes, but there are other policies that state DOTs can use as well. One such policy, rumble strips, can have a similar effect. Rumble strips alert “drivers that they are leaving the driving lane” through “raised or grooved patterns on the roadway” (Wilder, 2011, p. 5). “They provide [*sic*] driver with both an audible warning (rumbling sound) and a physical vibration”, and are “installed on the roadway shoulder, or on the centerline of undivided highways” (p. 5).

A recent analysis found that rumble strips (referred to as SHARDS or shoulder audible roadway delineators in New York) are both effective at reducing crashes on rural two-lane roads and provide a strong ROI. The study found that rumble strips reduce fatal run-off-road (ROR) crashes by 29 percent and injury ROR crashes by 29 percent. This reduction will result in an

ROI ranging from \$46.00 for every \$1.00 invested to \$37.00 for every \$1 invested, depending on the circumstances and type of treatment used. This is a strong ROI and policy makers should give it thorough consideration when investigating policy options to reduce crashes on rural two-lane highways.

5.3 Chevrons

Another policy that state DOTs can pursue to decrease crashes is installing chevrons on curves. Chevrons alert drivers to a curve that may not be easily seen and can decrease the frequency of a variety of crashes. Researchers analyzed data from Washington State and performed an economic cost benefit analysis (Srinivasan, 2009). They found that the installation of new chevron signs at a curve can reduce fatal crashes by 16 percent and provide a benefit-cost ratio range of \$8.60-\$45.90: \$1. The range depends on the cost assumption for installation (between \$160 and \$30 per sign).

5.4 Raised Retroreflective Pavement Markers

A final policy to consider implementing is the installation of raised retroreflective pavement markers (RRPMs). RRPMs “are delineation devices that are often used to improve preview distances and guidance for drivers in inclement weather and low-light conditions” (Bahar, et al., 2004, p. 1). Researchers analyzed their effectiveness at decreasing crashes and performed a cost benefit analysis. They found that RRPMs decrease all crashes by 54.3 percent and result in a benefit-cost ratio of \$13.16 for every \$1.00 invested. There are some minor differences between the methodology used in this study and the other studies. Most notably, this study selected a five percent discount rate, versus the seven percent rate used above. This difference (and some minor other differences) may reduce the accuracy of any comparison.

5.5 Comparison

Each of these policies is a unique method to decrease crashes and make the roadways safer. They all have specific circumstances in which they can be best utilized, so it is inappropriate to say that one policy should be used at the exclusion of the others. Nonetheless, a comparison of the cost-benefit ratio of each policy can be of significant informational value. Table 8 below compares the ratios. The result of the analyses is that wider edge lines result in an ROI comparable with the alternative policies. These results provide strong evidence to support the installation of wider edge lines on rural, two-lane highways.

Table 7: Comparative Benefit-Cost Ratios by Policy

Policy	Benefit-Cost Ratio
Wider Edge Lines	\$32.87-\$55.20 for every \$1.00 invested
Rumble Strips	\$37.00-\$46.00 for every \$1.00 invested
Chevrons	\$8.60-\$45.90 for every \$1.00 invested
RRPMs	\$13.16 for every \$1.00 invested

6.0 Recommendations

Rural highways are unsafe when compared to other road types. They account for a disproportionately large number of injury and fatal crashes. There are a variety of policies that state DOTs can pursue to address this issue, but one of the most cost effective is increasing the width of edge lines on rural two-lane highways.

Agencies can use the results herein to develop a policy for six inch edge lines on their rural, two-lane highways. Wider edge lines have been shown to reduce total crashes 15 to 30 percent, and fatal plus injury crashes 15 to 38 percent. In addition, the benefit-cost ratio for wide edge lines is \$33 to \$55 for each \$1 spent, which is similar to rumble strips. If an agency is considering installing rumble strips as a safety countermeasure but concerned about the potential noise or pushback from the bicycle community, wider edge lines appear to offer similar results but without the concerns often associated with shoulder rumble strips.

7.0 Concluding Thoughts

Many states have adopted wider edge lines on a variety of roads for a variety of reasons. The adoption has been slow and uncoordinated, without sound empirical findings to support their policy choice. Previous studies found indirect evidence to support the adoption of wider edge lines, but evidence showing direct reductions in crashes were difficult to provide due to data issues (lack of appropriate safety data, lack of enough miles of wide edge line treatments, and naïve analyses techniques). The recent analysis of data from three states provides the necessary evidence to support the adoption of wider edge lines on rural two-lane highways. Based on the results of the cost benefit analysis above, state DOTs can now have further reassurance that their actions are in the best economic interest of society as well.

In some states, wider edge lines are first employed on freeways and other high-speed divided highways. The higher-speed is typically used to justify the wider edge lines. The most recent crash analysis shows that wider edge lines may have not significant benefit on freeways and other high-speed divided highways. Perhaps the subtle change is overpowered by the already high design standards used for freeways and other high-speed divided highways.

Finally, since the safety benefits of wider edge lines are now better documented with rigorous statistical analyses, it would be beneficial if the MUTCD could be amended so that the minimum edge line width on rural two-lane highways was six inches. Agencies would then be able to implement the policy in a uniform and consistent manner.

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