

Investigating Safety Impact of Edgelines on Narrow, Rural Two-Lane Highways by Empirical Bayes Method

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Narrow, rural two-lane highways are mostly characterized by low design features, light traffic volumes with high crash rates, and particularly high fatal crash rates. About 5,000 mi of these highways are administered by the Louisiana Department of Transportation and Development. Run-off-roadway (ROR) crashes are the most common type of crashes on narrow, rural two-lane highways. Because the *Manual on Uniform Traffic Control Devices* does not require edgelines, edgelines are not found on many such highways because of their low traffic volumes. There are two main concerns for edgeline implementation on narrow two-lane highways: the potential increase in head-on collisions and the added maintenance cost to the already constrained annual maintenance budget. The second part of a study that evaluated the safety impact of edgelines on narrow, rural two-lane highways in Louisiana is presented. On the basis of data collected from 10 locations, the first part of the study proved that edgelines centralized the lateral position of vehicles. This second part of the study evaluated the safety performance before and after the implementation of edgelines on roadway segments selected from all Louisiana districts. By using the empirical Bayes method, the study showed that edgeline implementation significantly reduced expected crash frequencies. Edgeline implementation reduced ROR crashes as well as head-on crashes. The implementation of edgelines benefited primarily male drivers and young drivers. Because of the crash-decreasing trend observed in the 3-year period classified as the after period in this study, the final estimated crash modification factor was 0.85 with a standard deviation of 0.039. The high benefit–cost ratio strongly supports edgeline implementation on narrow, rural two-lane highways in Louisiana.

Improving highway safety is a critical issue facing the Louisiana Department of Transportation and Development (DOTD) because the state's traffic fatality rate (fatalities per 100 million vehicle miles traveled) has been consistently higher than the national average despite the improvements made in the past several years. In 2011 the national average fatality rate was 1.0 per 100 million vehicle miles traveled, whereas in Louisiana the average rate was 1.12. Road departure crashes are the most common type of crashes on two-lane highways, particularly on narrow, rural two-lane highways, which

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are generally characterized by low design features and light traffic volumes. As shown in Figure 1, about 40% of the total rural two-lane roadway mileage under the Louisiana DOTD has a pavement width of less than 22 ft and carries less than 20% of the vehicle miles traveled.

There were 12,467 crashes on rural two-lane highways in Louisiana in 2010. Approximately 34% of fatal crashes and 35% of fatalities occurred on rural two-lane highways in that same year. Run-off-roadway (ROR) or roadway departure crashes are the most common type of crashes on narrow two-lane highways; they account for approximately 60% of total crashes. Pavement marking is considered an inexpensive crash countermeasure to reduce roadway departure crashes because the marking provides visual guidance that helps to confine vehicles within the travel lane. The *Manual on Uniform Traffic Control Devices* (MUTCD) provides guidelines for the installation of edgelines. However, rural two-lane highways with narrow lane widths are not always required to have edgelines because of their low daily traffic volumes.

During the debate on whether edgelines should be implemented on all rural two-lane highways to enhance roadway safety regardless of lane width or annual average daily traffic, state engineers had two concerns. One was that the presence of edgelines might influence drivers to operate closer to the centerline and thus increase the risk of head-on and sideswipe crashes. The other concern was that the benefits of implementing edgelines would not be worth the added maintenance cost for an already constrained maintenance budget. To investigate the impact of edgelines, in 2005 the Louisiana Transportation Research Center sponsored a study investigating vehicle lateral position before and after edgeline installation (1). From the data collected on 10 segments from Louisiana DOTD District 3, the conclusions were as follows:

- With edgelines, centralization of a vehicle's position is more apparent during the night; this positioning reduces the risk of ROR and head-on collisions.
- Edgeline markings generally cause drivers to operate their vehicles away from the road edge, regardless of the highway alignment.

To answer the question of the extent of crash reduction by edgelines on narrow, rural two-lane highways, this second part of the study was conducted with a focus on the crash analysis before and after edgeline implementation. To investigate the financial feasibility of edgeline implementation, a benefit–cost analysis was also performed.

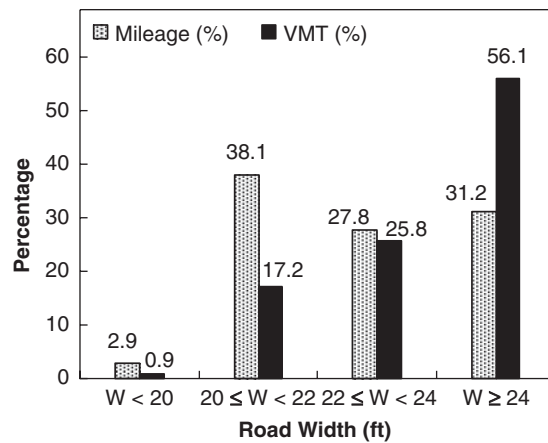


FIGURE 1 Distribution of rural two-lane highways by pavement width and percentage of traffic volume (VMT = vehicle miles traveled).

LITERATURE REVIEW

Pavement markings have traditionally been viewed by various transportation agencies as an inexpensive crash countermeasure. Unlike with other types of potential crash countermeasures, a limited number of studies have been conducted in the past on the safety impact of edgelines on narrow, rural two-lane highways. The results of the information reviewed on the effectiveness of edgelines can be summarized in three main categories: lateral position of the traveling vehicle, crash reduction, and benefit–cost analysis.

The earliest study on vehicle position was actually conducted in Louisiana by Thomas in 1958 on a 24-ft rural two-lane highway (2). The research concluded that the tendency of vehicles to move toward the center of edge-stripped pavements did not appear great enough to create any unusual hazard on a 24-ft-wide highway. In 1960 Thomas and Taylor repeated the study at different locations in Louisiana and reached almost the same conclusion (3). Other similar studies on vehicular lateral position were conducted by the Missouri State Highway Commission in 1969 and by Hassan in 1971 (4, 5). These two studies again reached similar conclusions. In 2000, research conducted by Steyvers and De Waard in the Netherlands employed video recording apparatus to observe vehicle position changes before and after edgeline installation on four unusually narrow rural highways with pavement widths between 13.5 ft and 14.8 ft (6). It was concluded that edgelines would provide a simple and effective way of inducing a more favorable lateral position on rural roads.

Musick researched a comparison of highway crash occurrence before and after edgeline markings on nine pairs of rural two-lane highways in Ohio in 1960 (7). The research revealed that edgeline placement resulted in a considerable reduction in fatal and injury crashes. A before-and-after study found that edgeline placement contributed nearly a 20% reduction in crashes. Basile found a similar trend when he conducted a before-and-after analysis on the highways in Kansas (8). The study concluded that edgelines contributed to a 78% reduction in fatalities, and crashes at intersections or driveways decreased considerably during both day and night.

In a 2005 study, Tsyganov et al. employed crash data from the Texas Department of Public Safety to evaluate the current relationship between highways with and without edgelines (9). The results

concluded that the expected crash reduction would be nearly 26%, and the best safety benefit was observed on horizontal curves and on highways with pavement widths of 18 to 20 ft. A study completed in 1991 by Miller quantified the benefit–cost ratios of edgelines for different roadway conditions (10). Analysis of crash data determined that pavement markings contributed a 60:1 benefit–cost ratio.

Research has repeatedly proved that the installation of edgeline markings reduces crash rates and improves highway safety. Some argue that if an edgeline 4 to 6 in. wide can contribute to highway safety, a wider edgeline may offer additional safety benefits. A benefit–cost analysis conducted by Hughes et al. determined an annual decrease of eight edgeline-related crashes for every 1,000 mi striped with wide (8-in.) edgelines (11). Cottrell's study in 1987 can be considered one of the earliest safety evaluations of wider edgelines (12). The results presented nearly a 14% reduction in both ROR and opposite-direction crashes.

Another study, from New Mexico, used 530 mi of rural two-lane highways (those having high crash rates) to estimate the edgeline impact on ROR and opposite-direction crash rates (13). The findings revealed that crash rates decreased approximately 10% at the treatment locations and 16% at the comparison sections. A recent study by Miles et al. evaluated the potential benefits of using wider and brighter edgeline markings (14). The results showed that safety improvement supported the use of wider edgelines for two-lane highways.

In the first edition of the *Highway Safety Manual* (HSM), there are crash modification factors (CMFs) for placing standard and wide edgeline markings on rural two-lane highways (the width of pavement is not mentioned) (15). The CMF value of edgeline placement from the HSM is within the range of 0.90 to 1.10. Although few investigations were conducted on the effectiveness of edgeline implementation more than two decades ago, no studies have been conducted on edgelines on narrow, rural two-lane highways with light daily traffic volume.

DATA

Rural two-lane highway segments with pavement width of less than 22 ft were selected from all Louisiana DOTD districts. Because of their low annual average daily traffic, these sections did not have and are not required by the MUTCD to have pavement edgelines.

Since changes occur each year on roadway segments, such as widening the pavement and upgrading to a multilane highway, after the initial segment selection, the research team verified each segment by reviewing images from the Louisiana DOTD biennial pavement condition survey. These changes are not always updated in time for the database. After a few segments were eliminated because they were either on a bridge or were upgraded to a wider lane width, the final selection was made as shown in Table 1. These segments vary in length following the Louisiana DOTD highway segmentation system to ensure that the most important attributes, such as pavement type and width and shoulder type and width, are uniform within each segment.

Edgelines were implemented on the selected segments between March and June 2008 by each Louisiana DOTD district and were verified by site visits (nearly 64%) during summer 2008 or by an imaging review. The crash data used in the analysis are from 2005 to 2011; that is, 3 years before (2005 to 2007) and 3 years after (2009 to 2011) the edgeline implementation.

TABLE 1 Summary of Segments Selected for Edgeline Implementation

DOTD District	Total Length (mi)	Number of Segments
02	1.38	1
03	31.96	9
04	6.06	2
05	24.75	4
07	12.51	2
08	4.84	2
58	1.17	1
61	7.85	3
62	19.12	4
Total	109.64	28

ANALYSIS METHOD

The empirical Bayes (EB) method is used to estimate the impact of the edgelines; the method combines the observed crash frequency with the predicted crash frequency to estimate the expected change in crashes. The EB method accounts for the effect of regression to the mean, changes in traffic volume, and other potential changes in the roadway features during the before and after time periods. This method is considered to be a statistically defensible method for safety evaluation (16). Specifically, it estimates safety effectiveness by examining the difference between observed crashes in the after time period and the expected crashes had treatments not been applied. The safety performance function (SPF) for rural two-lane highways from the first edition of the HSM is used (15).

The basic EB calculation steps are described as follows:

Step 1. Estimate the expected crashes before and after the edgeline implementation by the SPF:

$$\hat{E}(k_{iy}) = \text{AADT} \times L_i \times 365 \times 10^{-6} \times e^{(-0.312)} \times \prod \text{CMF}_j \quad (1)$$

where

$\hat{E}(k_{iy})$ = predicted total crash frequency for roadway segment i in year y given by the HSM,

AADT = annual average daily traffic,

L_i = length of roadway segment i (mi), and

CMF_j = crash modification factor for condition j that does not match base condition defined by HSM model.

The summation of the SPF estimates on segment i over 3 years before edgeline implementation, P_i , and 3 years after implementation, Q_i , is

$$P_i = \sum_{y=1}^3 \hat{E}(k_{iy}) \quad (2)$$

$$Q_i = \sum_{y=5}^7 \hat{E}(k_{iy}) \quad (3)$$

The ratio of the SPF estimates before and after edgeline implementation for segment i is

$$C_i = \frac{\sum_{y=5}^7 \hat{E}(k_{iy})}{\sum_{y=1}^3 \hat{E}(k_{iy})} = \frac{Q_i}{P_i} \quad (4)$$

Step 2. Estimate the expected number of crashes with the EB method, M_i , before edgeline implementation and the variance of M_i ,

$$M_i = w_i P_i + (1 - w_i) K_i \quad (5)$$

$$w_i = \frac{1}{1 + \frac{P_i}{k}} \quad (6)$$

$$k = \frac{0.236}{L} \quad (7)$$

where

K_i = total crash counts during the before period at site i ,

w_i = weight factor, and

k = overdispersion parameter.

The estimated overdispersion parameter is based on the negative binomial regression model, which is a function of the roadway segment length as specified in the HSM. The closer the overdispersion parameter is to zero, the more statistically reliable the SPF is.

The estimated variance of M_i is given by

$$\text{var}(M_i) = (1 - w_i) M_i \quad (8)$$

Thus,

$$\hat{M} = \sum_{i=1}^I M_i \quad (9)$$

$$\hat{\text{var}}(\hat{M}) = \sum_{i=1}^I \text{var}(M_i) \quad (10)$$

where

\hat{M} = sum of the expected number of crashes, M_i , before edgeline implementation;

$\hat{\text{var}}(\hat{M})$ = estimated variance of \hat{M} ; and

I = total number of selected sites for edgeline implementation.

Step 3. Estimate the number of EB-predicted crashes for the after time period and its variance.

$$\hat{\pi}_i = C_i M_i \quad (11)$$

where $\hat{\pi}_i$ equals the estimate of EB predicted crashes.

TABLE 2 Summary Results of EB Calculation

DOTD District	Section Length (mi)	Number of Control Sections	L_i	$\hat{\theta}$	SD ($\hat{\theta}$)	$\hat{\theta} + 3 * SD (\hat{\theta})$	$\hat{\theta} - 3 * SD (\hat{\theta})$
02	1.38	1	7	0.45	0.1975	1.04	-0.15
03	31.96	9	234	1.13	0.1069	1.45	0.82
04	6.06	2	23	0.56	0.1459	0.99	0.12
05	24.75	4	261	0.99	0.0894	1.26	0.73
07	12.51	2	41	0.74	0.1459	1.17	0.30
08	4.84	2	33	0.72	0.1612	1.20	0.22
58	1.17	1	7	0.71	0.3114	1.65	-0.22
61	7.85	3	50	0.54	0.0946	0.82	0.25
62	19.12	4	196	0.66	0.0632	0.85	0.48
All	109.64	28	852	0.84	0.0397	0.95	0.72

NOTE: SD = standard deviation.

$$\hat{\text{var}}(\pi_i) = C_i^2 \hat{\text{var}}(M_i) = C_i^2(1 - w_i)M_i \quad (12)$$

where $\hat{\text{var}}(\pi_i)$ equals the variance of the estimate of EB predicted crashes.

$$\hat{\pi} = \sum_{i=1}^I \pi_i \quad (13)$$

$$\hat{\text{var}}(\hat{\pi}) = \sum_{i=1}^I \text{var}(\hat{\pi}_i) \quad (14)$$

Step 4. Estimate the index of effectiveness of the edgeline, $\hat{\theta}$, and its variance with 95% confidence.

$$\hat{\theta} = \frac{L}{\hat{\pi} \left[1 + \frac{\hat{\text{var}}\{\hat{\pi}\}}{\hat{\pi}^2} \right]} \quad (15)$$

$$\sigma\{\hat{\theta}\} = \frac{\hat{\theta} \times \sqrt{\left(\frac{1}{L} + \frac{\hat{\text{var}}\{\hat{\pi}\}}{\hat{\pi}^2} \right)}}{1 + \frac{\hat{\text{var}}\{\hat{\pi}\}}{\hat{\pi}^2}} \quad (16)$$

where L is the total observed crash counts from the after time period and $\sigma\{\hat{\theta}\}$ equals the standard error of the index of effectiveness.

The calibration parameter introduced in Chapter 10 of the HSM is not used in the calculation since it is canceled in Equation 4 for the ratio calculation (15). The results of the calculation are given in Table 2. The effectiveness index for edgeline implementation is estimated as 0.84 with a standard deviation of 0.04.

CRASH CHARACTERISTICS

In addition to the effectiveness of the edgeline analysis, crash characteristics were also investigated. As shown in Figure 2, a general declining trend was observed not only for total crashes but also for property-damage-only (PDO) and injury crashes. The injury crashes

in the after period decreased by 19.6% and PDO crashes decreased by 9.5%.

It is interesting to see how the distribution of types of collisions changed between the before and after periods; this change is graphed in Figure 3. As expected, the highest reduction comes from single-vehicle crashes, which are the crashes targeted by the implemented countermeasure. Overall, all crash types display a decreasing trend except for left-turn crashes, which show an increasing trend.

Specifically, the number of single-vehicle crashes decreased by 13%, rear-end crashes decreased by 4%, and right-angle crashes decreased by 20%. The number of left-turn crashes increased by 16%. However, the decline in head-on crashes is very encouraging. Another important observation was the difference in crashes under different lighting conditions. A majority of the crashes happened in daylight, but the number of overall daylight crashes decreased by 14% and nighttime crashes decreased by 10% in the after period.

Figure 4 represents the crash reductions by surface condition. There was a 14.9% reduction in crashes in dry pavement surface conditions and 8.20% reduction in crashes in wet pavement surface conditions. One possible explanation for the difference is that edgeline markings in wet conditions may not be as visible as they are in dry conditions.

Driving errors such as wrong perceptions, slow reactions, and poor decision making are the products of a poor match between the capabilities of drivers and the demanded driving task. There are big variations in drivers' capacities as well as in their mental and physical conditions. Thus, a crash countermeasure could work differently for different drivers. The crashes incurred by male and female drivers are shown in Figure 5a and those crashes by age group are shown in Figure 5b.

About 52% of Louisiana's license holders are women. Although male drivers are generally involved in more crashes, they also drive more. The crash reduction by edgeline implementation is significant for male drivers but not for female drivers (5% of the records had no driver gender information). There are also differences in crash reduction by age. As seen in Figure 5b, the biggest reduction, about 17%, occurs with drivers age 24 years or younger. There is no reduction in crash rates for drivers between the ages of 55 and 65 years.

Figure 6 illustrates the impact of edgelines on drivers' distraction and type of violations from the crash data analysis. It appears that

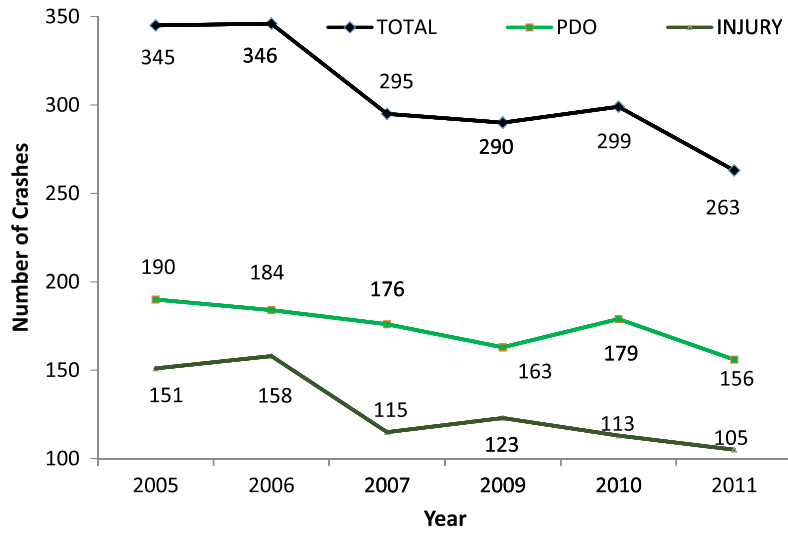


FIGURE 2 Crash distributions by severity and year.

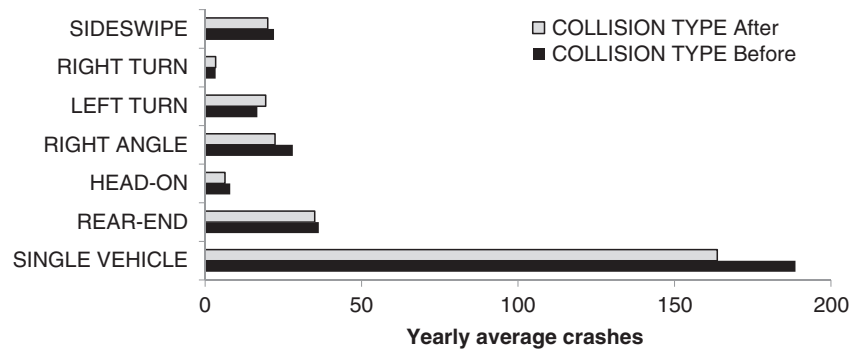


FIGURE 3 Distribution of changes in collision types.

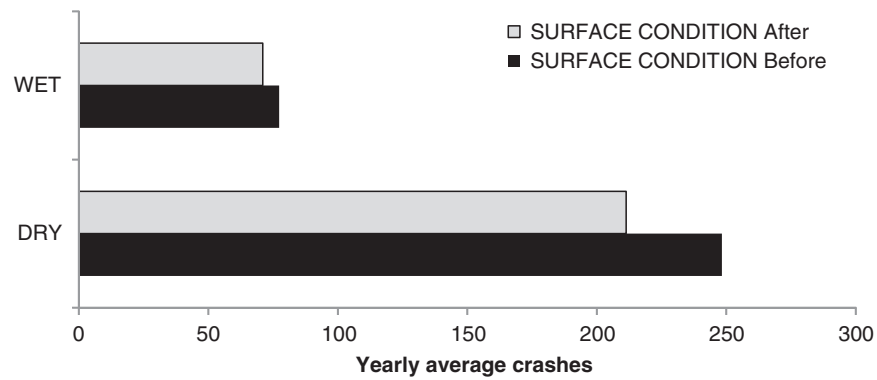


FIGURE 4 Crash reductions by surface conditions.

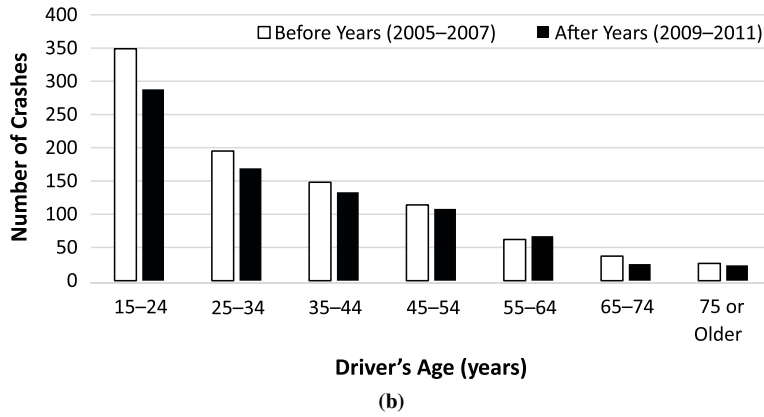
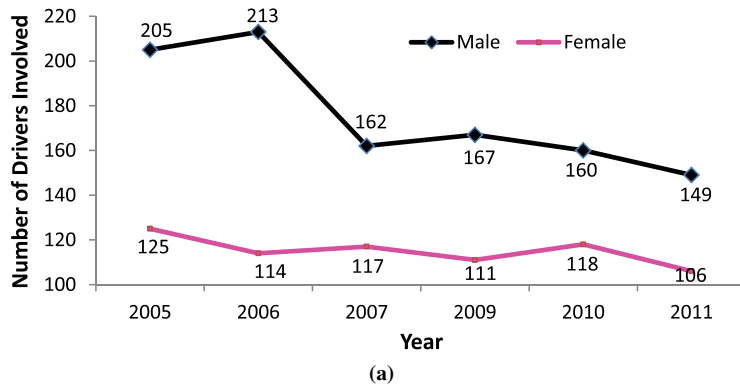


FIGURE 5 Change in numbers of crashes (a) by driver's gender and (b) by driver's age.

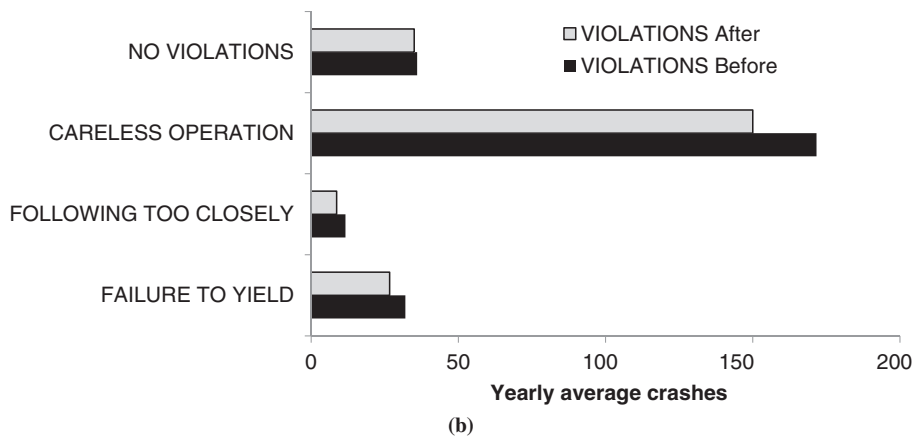
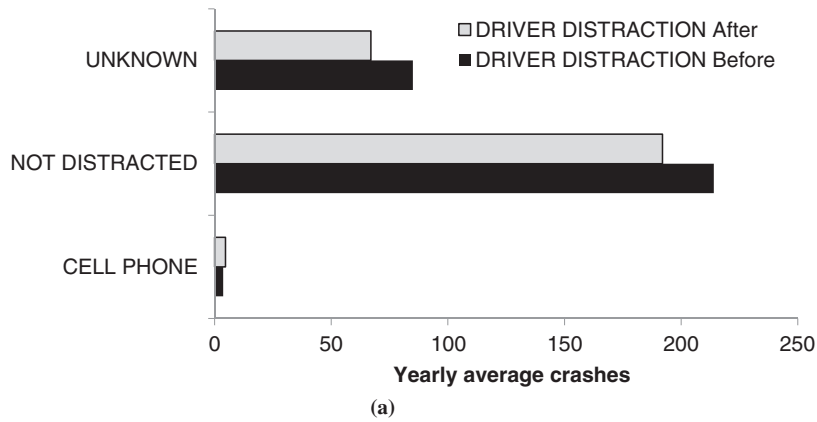


FIGURE 6 Impact of edgelines on (a) driver distraction and (b) type of driver violations.

TABLE 3 Decreasing Trend of Crashes on Louisiana Rural Two-Lane Highways

Year or Range	Number of Crashes, by Pavement Width				Total
	<20 ft	≥20 ft and <22 ft	22 ft	>22 ft	
2005	183	2,747	2,847	6,794	12,571
2006	163	2,741	2,891	7,041	12,836
2007	222	2,993	3,070	7,480	13,765
Average for 2005–2007	189	2,827	2,936	7,105	13,057
2009	260	2,686	2,965	6,816	12,727
2010	212	2,892	2,966	6,397	12,467
2011	206	2,796	2,910	6,496	12,408
Average for 2009–2011	226	2,791	2,947	6,570	12,534
Change (%)	19.58	–1.27	0.37	–7.53	–4.01

the edgeline installation resulted in a reduction in the crashes caused by distracted drivers and three major traffic violation types: careless operation, following too closely, and failure to yield.

DISCUSSION OF RESULTS

Although the results exhibit a decline in crashes, the overall crash reduction trend in the past few years should be considered. For the past several years (2009 to 2011), Louisiana, along with the entire country, has been experiencing a steady decline in annual fatal and total crash frequencies (17). In 2011, Louisiana had 630 fatal crashes, a 30% reduction from 2007. During the study period, the total crashes in the Louisiana DOTD roadway network were reduced by 5.6% from the before years (2005 to 2007) to the after years (2009 to 2011).

Table 3 gives annual crashes by pavement width on rural two-lane highways in Louisiana; a 4.01% crash reduction is shown for rural two-lane highways with all pavement widths and a 1.3% crash reduction for pavement widths less than 22 ft and greater than or equal to 20 ft during the study period. The study segments fall in this pavement width group.

As estimated by the EB method, the index of effectiveness for edgeline implementation on the selected narrow, rural two-lane highways is 0.84. After considering the overall crash reduction of 1.3% during the time period, the final estimated index of effectiveness for edgeline implementation would be 0.85 (0.84 + 0.01) with a standard deviation of 0.039; this finding means that the range of the estimation is between 0.73 and 0.96.

The cost for installing 6-in. edgelines varies depending on the cost of labor and materials. To develop the benefit–cost ratio for edgeline implementation, three unit costs were used in the calculation. The benefits were computed by the crash reduction at three severity levels. According to the Louisiana data, the average cost was \$4,376,304 for a fatal crash, \$137,670 for an injury crash, and \$3,292 for a PDO crash. Installing edgelines reduces crashes, and thus the benefits are estimated by crash costs as shown below:

<i>Benefit</i>	<i>Injury Crashes</i>	<i>PDO Crashes</i>
Reduction in crash numbers	83	52
Benefit from a single crash reduction (\$)	137,670	3,292
Total benefits (\$)	11,597,794	

TABLE 4 Estimated Benefit–Cost Ratio for Edgeline Installation

Cost	Treatment		
	Paint (DOTD)	Paint (contractor)	Thermoplastic (contractor)
Per lane mile (\$)	450	700	2,800
Total (\$)	98,676	153,496	613,984
Benefit–cost ratio	117.53	75.56	18.89

Because of the lack of SPF models for fatal and injury crashes, the observed reduction of crashes was used for benefit calculations. The estimated benefit–cost ratio for edgeline installation ranged from 18.89 to 117.53 on the basis of the labor and material costs shown in Table 4.

CONCLUSION

This project clearly demonstrates the safety benefits of edgeline implementation on narrow, rural two-lane highways in Louisiana. The expected total crash reduction is 15%. The estimated range of crash reduction (0.73, 0.96) is less than 1, indicating a high level of certainty. The reduction in head-on crashes can ease the concern over edgeline implementation on narrow two-lane roadways. Also, the implementation of edgelines mainly benefits male and young drivers. It was also found that implementation of edgelines helped reduce the variation in operating speed based on crash data analysis. The encouraging benefit–cost ratio suggests that edgelines be installed at segments with high ROR crash rates even if the MUTCD does not warrant their implementation because of the traffic volume.

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The Low-Volume Roads Committee peer-reviewed this paper.