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7. Author(s) Xiaoduan Sun, Ph.D., P.E. Subasish Das	8. Performing Organization Report No. University of Louisiana at Lafayette	
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The previous 2011 study “Safety Improvement from Edge Lines on Rural Two-Lane Highways” analyzed the crash data of three years before and one year after edge line implementation by using the latest safety analysis statistical method. It concluded that placing pavement edge lines on rural two-lane highways in Louisiana can not only change the lateral positions of the vehicles but also reduce crashes. The Crash Modification Factor (CMF) for edge line on narrow, rural two-lane highways is 0.78. Considering the decreasing trend in crashes in the state for the past three years, the modified CMF is 0.83, which implies that, on average, implementing edge lines can reduce 17% of crashes.

As an extension of the 2011 project, this study not only used two more years of crash data for the after time period but also applied the Empirical Bayes (EB) method in the analysis to estimate the crash reduction factors. Moreover, crash characteristics analysis is performed in this study to compare the difference before and after edge line implementation. Additionally, this project performed benefit and cost analysis.

By considering the safety trend in Louisiana, the final estimated CMF is 0.85, which means there is a 15% expected crash reduction in edge line implementation on narrow, rural two-lane highways. The statistically estimated standard deviation for the CMF is 0.039. The crash reduction is consistent in all crash types and particularly significant in single vehicle crashes. Most of single vehicle crashes are ROR crashes, which is the exact type of crash targeted by edge line implementation. The benefits overwhelmingly offset the cost with edge line implementation. The most conservative estimation for benefit and cost ratio is 19.

This project recommends the use of edge lines on narrow rural two-lane highways whenever it is financially feasible and operationally feasible.

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Assistant Secretary
Operations

A Comprehensive Study on Pavement Edge Line Implementation

by

Xiaoduan Sun, Ph.D., P.E.
Professor

Subasish Das
Ph.D. Student

Civil Engineering Department
University of Louisiana at Lafayette
254 Madison Hall
100 Rex Street
Lafayette, LA 70504

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Louisiana Transportation Research Center

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ABSTRACT

The previous 2011 study “Safety Improvement from Edge Lines on Rural Two-Lane Highways” analyzed the crash data of three years before and one year after edge line implementation by using the latest safety analysis statistical method. It concluded that placing pavement edge lines on rural two-lane highways in Louisiana can not only change the lateral positions of the vehicles but also reduce crashes. The Crash Modification Factor (CMF) for edge line on narrow, rural two-lane highways is 0.78. Considering the decreasing trend in crashes in the state for the past three years, the modified CMF is 0.83, which implies that, on average, implementing edge lines can reduce 17% of crashes.

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By considering the safety trend in Louisiana, the final estimated CMF is 0.85, which means there is a 15% expected crash reduction in edge line implementation on narrow, rural two-lane highways. The statistically estimated standard deviation for the CMF is 0.039. The crash reduction is consistent in all crash types and particularly significant in single vehicle crashes. Most of single vehicle crashes are ROR crashes, which is the exact type of crash targeted by edge line implementation.

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This project recommends the use of edge lines on narrow rural two-lane highways whenever it is financially feasible and operationally feasible.

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IMPLEMENTATION STATEMENT

Louisiana has about 5,600 miles of narrow, rural two-lane highways. Inexpensive and feasible countermeasures are required to be proposed to reduce the higher percentage of crashes and fatalities associated with this type of highway. The findings of this project present the outcome of an inexpensive countermeasure. The study recommends that use of edge lines on narrow rural two-lane highways whenever it is financially feasible and operationally feasible. The provided recommendations should help DOTD’s future plan on improving the safety of rural two-lane highways.

Particularly, each DOTD district can use the outcomes of this research in operating and maintaining roadways under their administration.

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INTRODUCTION

Highway safety is a crucial issue in Louisiana. Each year, approximately 150,000 crashes occur, over 90,000 of which are on the state-maintained highway system. In 2011, 677 people were killed and 70,354 were injured in highway crashes in Louisiana. Rural two-lane highways in this state carry one-third of the total vehicle miles traveled (VMT) and have experienced a considerably high percentage of fatal crashes. There were 12,467 crashes on rural two-lane highways in Louisiana in 2010. In that same year, approximately 34% of fatal crashes and 35% of fatalities in the entire state occurred on rural two-lane highways.

Road departure crashes are considered one of the most frequent and expensive types of crashes in the United States *[1]*. These crashes are more frequent on rural highways, accounting for 60% of total crashes on rural two-lane roads *[2]*. Appropriate pavement markings is an inexpensive crash countermeasure to reduce road departure crashes. An edge line generally provides visual guidance, which helps to confine vehicles within the traveled lane to avoid road departure. The impact of edge lines were documented in a number of studies. The Manual on Uniform Traffic Control Devices (MUTCD) provides guidelines for the installation of edge lines. However, rural two-lane highways with narrow lane width are not always required to have edge lines. One of the major concerns is that the presence of edge lines may influence drivers to operate closer to the centerline which then increases the risks of head-on and sideswipe crashes *[3]*. While DOTD makes efforts to comply with the new MUTCD requirement, concerns arise on safety and benefit-costs of edge lines on narrow, rural two-lane highways.

To investigate the impact of edge lines, the Louisiana Transportation Research Center (LTRC) sponsored a study in 2005 investigating the vehicular lateral position with edge line installation, “Impact of Edge Lines on Safety of Rural Two-Lane Highways.” This project concluded that:

- With edge lines, centralization of a vehicle’s position is more apparent during nighttime, which reduces the risk of run-off-road (ROR) and head-on collisions.
- Edge line markings generally cause drivers to operate their vehicles away from the road edge, irrespective of the highway alignment.

The 2005 study also states that the magnitude of the impact of edge line markings is influenced by highway width, operating speed, time of day, frequency of heavy vehicles, pavement condition, highway alignment, and traffic volume from the opposite direction. These conclusions were drawn based on the analysis of vehicular lateral position data collected from 10 sites on the narrow, rural two-lane highways that are within the DOTD District 03.

Using the latest safety analysis statistical method, another LTRC sponsored study, "Safety Improvement from Edge Lines on Rural Two-Lane Highways," completed in 2011, analyzed the crash data before and after edge line implementation, and concluded that placing pavement edge lines on rural two-lane highways in Louisiana can not only change vehicles' lateral positions but can also reduce crashes *[4]*. The CMF for edge lines on narrow, rural two-lane highways is 0.78. Considering the decreasing trend in crashes in the state for the past three years, the modified CMF is 0.83, which implies that, on average, implementing edge lines can reduce 17% of crashes.

As stated in the 2011 project report, pavement markings have traditionally been viewed by various transportation agencies as an inexpensive crash countermeasure for improving highway safety. Unlike other types of potential crash countermeasures, there has been a limited number of studies conducted in the past on the safety impact of edge lines on narrow, rural two-lane highways. The results of the information reviewed on the effectiveness of edge lines can be summarized in three main categories: lateral position of the travelling vehicle, crash reduction, and benefit-cost analysis. The following review is the same as in the 2011 report.

The earliest study on vehicle position was actually conducted in Louisiana by I. L. Thomas in 1958 on a 24-ft. rural two-lane highway in the state. He wanted to see if a broken or continuous line at various distances from the pavement edge had any sort of impact on vehicles' lateral position. The research concluded that the tendency of vehicles to move towards the center of edge-striped pavements did not appear considerably large enough to create any unusual hazard on a 24-ft. wide highway *[5]*. In 1960, the same author repeated the study at different locations in Louisiana, which yielded the same conclusion *[6]*. Other similar studies on the vehicular lateral position were conducted by the Missouri State Highway Department in 1969 and Z. Y. Hassan in 1971 *[7, 8]*. These two studies again gave the similar conclusions. In 2000, research conducted by F. J. Steyvers et al. in the Netherlands used video recording equipment to observe vehicles' position changes before and after edge line installation on four unusually narrow rural highways with pavement widths between 13.5 ft. and 14.8 ft. *[9]*. It was observed that drivers took a more central position and approached the road edges less frequently when an edge line was present. Interestingly, no problems were encountered with oncoming vehicles on the edge lined highways as the vehicles traveling in both directions yielded to the side while passing.

J. V. Musick made a comparison of highway crash occurrences before and after edge line markings on nine pairs of rural two-lane highways in Ohio in 1960. The research showed that edge line placement resulted in a considerable reduction in fatal and injury crashes *[10]*. A before and after study identified that edge line placement contributed nearly a 20% reduction in crashes. Fatalities and injuries reduced by 37%, and nighttime crashes decreased by 35%. A. J. Basile found a similar trend to Musick's study when he conducted a before and after analysis on the highways of Kansas in 1962 *[11]*. In Kansas, edge lines were added to most of the rural two-lane highways with a pavement width of 20 to 26 ft. and a minimum average daily traffic (ADT) of 1,000 vehicles per day (vpd). The study showed that edge lines contributed to a 78% reduction in fatalities, and crashes at intersections or driveways were considerably decreased for both day and night.

In a 2005 study, A. R. Tsyganov et al. studied crash data from the Texas Department of Public Safety to evaluate the current relationship between highways with and without edge lines *[12]*. They reviewed data from nearly 10,000 crashes on rural two-lane highways for a four-year time span. Lane width, shoulder width, and ADT were also considered as significant attributes in the study. 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. The researchers described that the decrease in speeding-related crashes at night might be a result of improving the driver's perception of the travel path and speed of the vehicle. A study completed in 1991 by T. R. Miller quantified the benefit-cost ratios of edge lines for different roadway conditions *[13]*. Analyzed crash data determined that pavement markings contributed a 60:1 benefit-cost ratio. Miller showed that, even on rural two-lane roads with an ADT as low as 500 VPD, edge lines provided a benefit-cost ratio of 17:1.

Research has repeatedly proven that the installation of edge line markings reduces crash rates and improves highway safety. Some argue that if a 4- to 6-in. wide edge line can contribute to highway safety, then a wider edge line may offer additional safety benefits. A benefit-cost analysis conducted by W. E. Hughes et al. determined an annual decrease of eight edge line-related crashes for every 1,000 miles striped with wide (8-in.) edge lines *[14]*.To compare the general low cost of edge line markings with the overall cost of installing and maintaining roadways, it would be a reasonable step for the Department of Transportation (DOT) to investigate the potential improvements in safety from installing wider pavement markings. B. H. Cottrell's study in 1987 can be considered as one of the earliest safety evaluations of wider edge lines. The study analyzed crash data from three rural two-lane highways in Virginia *[15]*. At the three test sections, the treatment sites were striped with 8-in. wide edge lines, and the comparison sites were restriped with 4-in. wide edge lines. The before and after study considered crash data from three years before and two years after placing the treatment. That study specifically focused on ROR crashes and the researcher theorized that a significant reduction in ROR crashes would warrant the use of wider edge lines. The result showed nearly a 14% reduction in both ROR and opposite-direction (OD) crashes. But crash reductions from wider edge lines were not statistically significant when compared to the comparison sites. At the end, the researcher concluded that there was no substantial proof to consider that 8-in. wide edge lines usage significantly reduced the investigated crash rates.

Another study from New Mexico by J. W. Hall in 1987 used 530 miles of rural two-lane highway to evaluate the ROR and OD crash rates *[16]*. The study applied 8-in. edge lines on 176 miles of the studied roadway, and the remaining sections used 6 in. for comparison purposes. The findings showed that crash rates decreased approximately 10% at the treatment locations and 16% at the comparison sections.

A recent 2010 study by J. D. Miles et al. evaluated the potential benefits of using wider and brighter edge line markings *[17]*. The crash data analysis conducted in the study supports the implementation of wide edge line pavement markings to improve safety along rural highways.

In the recently published first edition of the Highway Safety Manual (HSM), there are CMFs for placing standard and wide edge line markings on rural two-lane highways (without mentioning the width of pavement) *[18]*.The CMF value of the edge line placement (from HSM) is within the range of 0.90 to 1.10. However, this CMF value from HSM cannot be used directly. Although investigations were conducted on the effectiveness of edge line implementation as reviewed above, none of these studies were done for the narrow, rural two-lane highways in Louisiana.

There is a need to continue the 2011 study not just with more crash data but also with the well accepted crash analysis methodology. It is important to investigate crash characteristics analysis of before and after years and benefit-cost ratio for edge line implementation on narrow, rural two lane highways.

OBJECTIVE

The goal of this project was to investigate the safety impact of pavement markings on rural two-lane highways in Louisiana. Specifically, the research objectives were:

- Conduct a complete before-and-after crash analysis with three years before and three years after crash data to estimate the crash reduction factors with EB method.
- Conduct crash characteristics analysis.
- Conduct benefit-cost analysis.

SCOPE

To meet the objectives of this project, this study was conducted on selected narrow, rural two-lane highways with pavement width less than 22 ft. from all DOTD districts. It was done with the collaboration of all DOTD districts for edge line implementation. The annual crash frequencies of six years (2005, 2006, 2007 as the "before period," and 2009, 2010, 2011 as the "after period") from each site were used. The improved safety prediction and Empirical Bayes (EB) methods are used in the analysis.

METHODOLOGY

The study consists of three basic steps: selection of the segments, edge line implementation, and before-after crash analysis. Since the first two steps are already described in detail in the 2011 study report, in this section focus will be given to the before and after study with EB method, thorough analysis on the traffic flow characteristics, crash and driver characteristics, correlation between the contributing factors, and benefit-cost analysis.

Selection of Segment and Edge Line Implementation

As in the report "Safety Improvement from Edge Lines on Rural Two-Lane Highways," the total length of the study sections was 114.12 miles *[4]*. After investigating the condition of pavement markings, two control sections were excluded from this study due to the fading edge lines. The final list of the analyzed segments is given in Table 1.

Table 1
Section length and no. of control sections of the districts

DOTD District	Section Length	No. of Control Sections
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
Average	**109.64**	**28**

Before and After Crash Analysis

The objective of an unbiased observational before-after study is to evaluate a treatment where the highways and facilities are unchanged (including AADT) except for the implementation of the treatment. However, it is impossible to control the changes of other factors in a highway safety study. Theoretically speaking, the true impact of a treatment should be the difference between the predicted safety after the treatment and the predicted safety in the after period if the treatment were not implemented. Two methods are used in the analysis.

Improved Before and After Crash Analysis

To account for the change in traffic volume, the following procedure, introduced by E. Hauer, was used in estimating the unbiased crash changes before and after installation of the edge line *[19]*.

Step One: Estimating the safety if the edge line was not installed during the after period, $\hat{\pi}$, and the safety with the edge line project $\hat{\lambda}$

$$\hat{\lambda} = N \quad (1)$$

$$\hat{\pi} = \hat{r}_{tf} K \quad (2)$$

where,

$\hat{\lambda}$ = Estimated expected number of crashes in the after time period with the edge line

N = Observed annual crashes after edge line project

$\hat{\pi}$ = Estimated expected number of crashes in the after period without the edge line

K = Observed annual crashes before the edge line project

$\hat{r}_{tf}$ = Traffic flow correction factor

$= \dfrac{\hat{A}_{avg}}{\hat{B}_{avg}}$

$\hat{A}_{avg}$ = Average traffic flow during the after period

$\hat{B}_{avg}$ = Average flows during the before period

The results of this application are listed in Table 2.

Table 2
Results from the first step

DOTD District	Section Length	No. of Control Sections	$\hat{\lambda}$	$\hat{A}_{avg}$	$\hat{B}_{avg}$	$\hat{r}_{tf}$	$\hat{\pi}$
02	1.38	1	7	1,333	880	1.51	17
03	31.96	9	234	32,967	34,023	0.97	214
04	6.06	2	23	3,187	2,753	1.16	42
05	24.75	4	261	20,200	18,800	1.07	260
07	12.51	2	41	3,977	4,160	0.96	62
08	4.84	2	33	4,047	3,693	1.1	46
58	1.17	1	7	3,967	5,100	0.78	9
61	7.85	3	50	7,923	7,290	1.09	93
62	19.12	4	196	31,270	27,897	1.12	304
All	**109.64**	**28**	**852**	**108,871**	**104,596**	**1.04**	**1,026**

Step Two: Estimating the variance $\hat{VAR}\{\hat{\pi}\}$ and $\hat{VAR}\{\hat{\lambda}\}$

$$\hat{VAR}\{\hat{\lambda}\} = N \tag{3}$$

$$\hat{VAR}\{\hat{r}_{tf}\} = \left(\hat{r}_{tf}\right)^2 \left(v^2\{\hat{A}_{avg}\} + v^2\{\hat{B}_{avg}\}\right) \tag{4}$$

$$\hat{VAR}\{\hat{\pi}\} = \left(r_d\right)^2 \left[\left(\hat{r}_{tf}\right)^2 K + K^2\, \hat{VAR}\{\hat{r}_{tf}\}\right] \tag{5}$$

where,

$\hat{VAR}\{\hat{\lambda}\}$ = Estimated variance of $\hat{\lambda}$

r_d = Ratio of time duration of after period to time duration of before period

v = The percent coefficient of variance for AADT estimates

$$= \left(1 + \frac{7.7}{(\text{number of count-days})} + \frac{1650}{AADT^{0.82}}\right) \times 0.01$$

(Number of count-days is considered as '3' in calculation.)

$\hat{VAR}\{\hat{\pi}\}$ = Estimated variance of $\hat{\pi}$

The results of this application are listed in Table 3.

Table 3
Results from the second step

DOTD District	Section Length	No. of Control Sections	$\hat{VAR}\{\hat{\lambda}\}$	$v\{\hat{A}_{avg}\}$	$v\{\hat{B}_{avg}\}$	$\hat{VAR}\{\hat{r}_{tf}\}$	$\hat{VAR}\{\hat{\pi}\}$
02	1.38	1	7	0.080865	0.099201	0.037348	30
03	31.96	9	234	0.038922	0.038839	0.002845	347
04	6.06	2	23	0.057783	0.060604	0.009435	61
05	24.75	4	261	0.040532	0.040827	0.003789	502
07	12.51	2	41	0.054110	0.053442	0.005330	82
08	4.84	2	33	0.053848	0.055266	0.007204	64
58	1.17	1	7	0.054148	0.050708	0.003348	8
61	7.85	3	50	0.046147	0.046888	0.005142	138
62	19.12	4	196	0.039067	0.039400	0.003862	624
All	**109.64**	**28**	**852**	**0.0368**	**0.0369**	**0.00295**	**3888**

Step Three: Estimating the crash $\hat{\delta}$ difference and the ratio $\hat{\theta}$

$$\hat{\delta} = \hat{\pi} - \hat{\lambda} \tag{6}$$

$$\hat{\theta} = \frac{\left(\frac{\hat{\lambda}}{\hat{\pi}}\right)}{\left[1 + \frac{\hat{VAR}\{\hat{\pi}\}}{\hat{\pi}^2}\right]} \tag{7}$$

where,

$\hat{\delta}$ = Estimated safety impact of the project

$\hat{\theta}$ = Estimated unbiased expected crash modification factor

The results of this application are listed in Table 4.

Table 4
Results from the third step

DOTD District	Section Length	No. of Control Sections	$\hat{\delta}$	$\hat{\theta}$
02	1.38	1	10	0.37304
03	31.96	9	-20	1.08524
04	6.06	2	19	0.52932
05	24.75	4	-1	0.99645
07	12.51	2	21	0.64748
08	4.84	2	13	0.69633
58	1.17	1	2	0.70787
61	7.85	3	43	0.52919
62	19.12	4	108	0.64041
All	**109.64**	**28**	**174**	**0.82812**

Step Four: Estimating the standard deviation of $\hat{\delta}$ and $\hat{\theta}$

$$\hat{\sigma}\{\hat{\delta}\} = \sqrt{(V\hat{A}R\{\hat{\lambda}\} + V\hat{A}R\{\hat{\pi}\})} \tag{8}$$

$$\hat{\sigma}\{\hat{\theta}\} = \frac{\hat{\theta} \times \sqrt{\left(\frac{V\hat{A}R\{\hat{\lambda}\}}{\hat{\lambda}^2} + \frac{V\hat{A}R\{\hat{\pi}\}}{\hat{\pi}^2} \right)}}{1 + \frac{V\hat{A}R\{\hat{\pi}\}}{\hat{\pi}^2}} \tag{9}$$

The results of this application are listed in Table 5.

Table 5
Results from the fourth step

DOTD District	Section Length	No. of Control Sections	$\hat{\sigma}\{\hat{\delta}\} = \sqrt{variance}$	$\hat{\sigma}\{\hat{\theta}\} = \sqrt{variance}$
02	1.38	1	6.08276	0.16785
03	31.96	9	24.10394	0.11725
04	6.06	2	9.16515	0.14294
05	24.75	4	27.62245	0.10495
07	12.51	2	11.09054	0.13556
08	4.84	2	9.84886	0.16631
58	1.17	1	3.87298	0.31668
61	7.85	3	13.71131	0.09877
62	19.12	4	28.63564	0.06926
All	**109.64**	**28**	**64.83945**	**0.05785**

Empirical Bayes Method

The EB method is a statistical method that combines the observed crash frequency with the predicted crash frequency using the Safety Performance Function (SPF) to calculate the expected crash frequency for a site of interest. This method can account for the effect of regression-to-the-mean along with changes in traffic volume and other changes not due to the treatment in crash frequencies. It has been considered a statistically defensible safety evaluation tool in observational before-after studies for more than two decades *[20]*. In an EB method, SPFs are used to estimate the expected crash frequencies at the treated sites had treatments not been applied *[19]*. Generalized linear regression models, specifically negative binomial regression models, are often used to derive the SPFs *[21]*. It's important to note that, in this evaluation, safety performance functions were calibrated for each year of the before and after periods rather than just for each period.

Step One: The first step was to develop a SPF. Researchers used the SPF of HSM for rural two-lane highway segments as given below:

$$\hat{E}(k_{iy}) = AADT \times L \times 365 \times 10^{-6} \times e^{(-0.312)} \tag{10}$$

where,
$E(k_{iy})$= predicted total crash frequency for roadway segment base conditions;
AADT = average annual daily traffic volume (vehicles per day);
L = length of roadway segment (miles).

After developing the SPF function, researchers estimated the expected number of crashes for each year in the before period at each treatment site.

Step Two: The second step was to compute the sum of the annual SPF predictions for each treatment site during the before period by:

$$P_i = \sum_{y=1}^{y_{0i}-1} \hat{E}(k_{iy}) \quad (11)$$

where, y_{0i} denotes the year during which the edge line was installed at site i.

The results of first two steps are listed in Table 6.

Table 6
Results from the first two steps

DOTD District	Section Length	No. of Control Sections	P_i
02	1.38	1	1
03	31.96	9	82
04	6.06	2	8
05	24.75	4	60
07	12.51	2	12
08	4.84	2	12
58	1.17	1	5
61	7.85	3	14
62	19.12	4	72
All	**109.64**	**28**	**266**

Step Three: The third step was to obtain an estimate of the expected number of crashes (M_i) before implementation of the countermeasure at each treatment site and an estimate of variance of M_i. The estimate M_i was given by combining the sum of the annual SPF predictions during the before period (P_i) with the total count of crashes during the before period as follows:

$$M_i = w_i P_i + (1 - w_i) K_i \tag{12}$$

where, K_i is the total crash counts during the before period at site i and the weight w_i is given by:

$$w_i = \frac{1}{1 + \frac{P_i}{k}} \tag{13}$$

where, k is the estimated over dispersion parameter of the negative binomial regression model that is a function of the roadway segment length as specified in HSM. The closer the over dispersion parameter is to zero, the more statistically reliable the SPF is. The value is calculated as:

$$k = \frac{0.236}{L} \tag{14}$$

where,

k = over dispersion parameter;

L = length of roadway segment (miles).

An estimated variance of M_i is given by:

$$Var(M_i) = (1 - w_i) M_i \tag{15}$$

As the relationship is linear, the M_i value of each district was calculated by summing up all consecutive control sections.

$$\hat{M} = \sum_{i=1}^{I} M_i \tag{16}$$

$$V\hat{a}r(\hat{M}) = \sum_{i=1}^{I} Var(M_i) \tag{17}$$

The results of step three are shown in Table 7.

Table 7
Results from the third step

DOTD District	**Section Length**	**No. of Control Sections**	M_i	$Var(M_i)$
02	1.38	1	10	8.08
03	31.96	9	209	199.52
04	6.06	2	35	33.56
05	24.75	4	241	239.13
07	12.51	2	64	63.21
08	4.84	2	41	40.72
58	1.17	1	12	11.23
61	7.85	3	83	81.04
62	19.12	4	263	258.63
All	**109.64**	**28**	**958**	**935.24**

Step Four: The fourth step was to determine SPF predictions $\hat{E}(k_{iy})$ for each year in the after period at each treatment site, and compute C_i (the ratio of the sum of the annual SPF predictions for the after period, Q_i and the sum of the annual SPF predictions for the before period, P_i).

$$C_i = \frac{\sum_{y=y_{Oi}+1}^{y} \hat{E}(k_{iy})}{\sum_{y=1}^{y=y_{Oi}-1} \hat{E}(k_{iy})} = \frac{Q_i}{P_i} \tag{18}$$

Step Five: The fifth step was to obtain the predicted crashes and its estimated variance during the after period that would have occurred without implementing the countermeasure. The predicted crashes ($\hat{\pi}_i$) are given by:

$$\hat{\pi}_i = C_i M_i \tag{19}$$

The estimated variance of ($\hat{\pi}_i$) is given by:

$$V\hat{a}r(\pi_i) = C_i^2 V\hat{a}r(M_i) = C_i^2 (1 - w_i) M_i \tag{20}$$

Step Six: The sixth step was to compute the sum of the predicted crashes over all sites in a treatment group of interest and its estimated variance by:

$$\hat{\pi} = \sum_{i=1}^{I} \pi_i \tag{21}$$

$$V\hat{a}r(\hat{\pi}) = \sum_{i=1}^{I} Var(\hat{\pi}_i) \tag{22}$$

where, *i* is the total number of sites in a treatment group of interest.

The results of step four to step six are shown in Table 8.

Table 8
Results from the fourth to sixth steps

DOTD District	Section Length	No. of Control Sections	C_i	$\hat{\pi}$	$Var(\hat{\pi})$
02	1.38	1	1.52	15	18.55
03	31.96	9	0.96	205	197
04	6.06	2	1.13	40	44.34
05	24.75	4	1.08	260	280.6
07	12.51	2	0.83	55	46.62
08	4.84	2	1.17	45	49.74
58	1.17	1	0.80	9	6.80
61	7.85	3	1.21	93	103.91
62	19.12	4	1.13	294	324.34
All	**109.64**	**28**	**1.06**	**1,016**	**1,071.90**

Step Seven: The seventh step was to compute the sum of the observed crashes over all sites in a treatment group of interest by:

$$L = \sum_{i=1}^{I} L_i \tag{23}$$

where, L_i is the total crash counts during the after period at site i.

Step Eight: The index of effectiveness of the countermeasure was estimated by:

$$\hat{\theta} = \frac{L}{\hat{\pi}\left[1 + \frac{\hat{VAR}\{\hat{\pi}\}}{\hat{\pi}^2}\right]} \tag{24}$$

where, $\hat{\theta}$= Estimated unbiased expected crash modification factor.

Step Nine: The ninth step was to compute the estimated variance and standard error of the index of effectiveness and the approximate 95% confidence interval for θ. The estimated standard error of the index of effectiveness are given by:

$$\hat{\sigma}\{\hat{\theta}\} = \frac{\hat{\theta} \times \sqrt{\left(\frac{1}{L} + \frac{\hat{Var}\{\hat{\pi}\}}{\hat{\pi}^2}\right)}}{1 + \frac{\hat{Var}\{\hat{\pi}\}}{\hat{\pi}^2}} \qquad (25)$$

The results of step seven to step nine are shown in Table 9.

Table 9
Results from the seventh to ninth steps

DOTD District	Section Length	No. 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**

Traffic Flow Characteristics

In addition to the CMF development, traffic characteristics were also analyzed to see if significant changes exist between the before and after time periods. It is noted the AADT increased by 4% on average during the after period. The density plot of AADT is presented in Figure 1, which indicates two spikes in AADT during the after period. Figure 2 represents the density plot of estimated operating speed in before-after periods, which shows densities of the moderate speed (50-65mph) are increased in the after years. Edge lines helped the drivers to keep their vehicles in proper lane; at the same time, drivers increase the speed because of the nature of behavioral adaptation. The box and whisker plot in Figure 3 clearly shows the increased average speed.

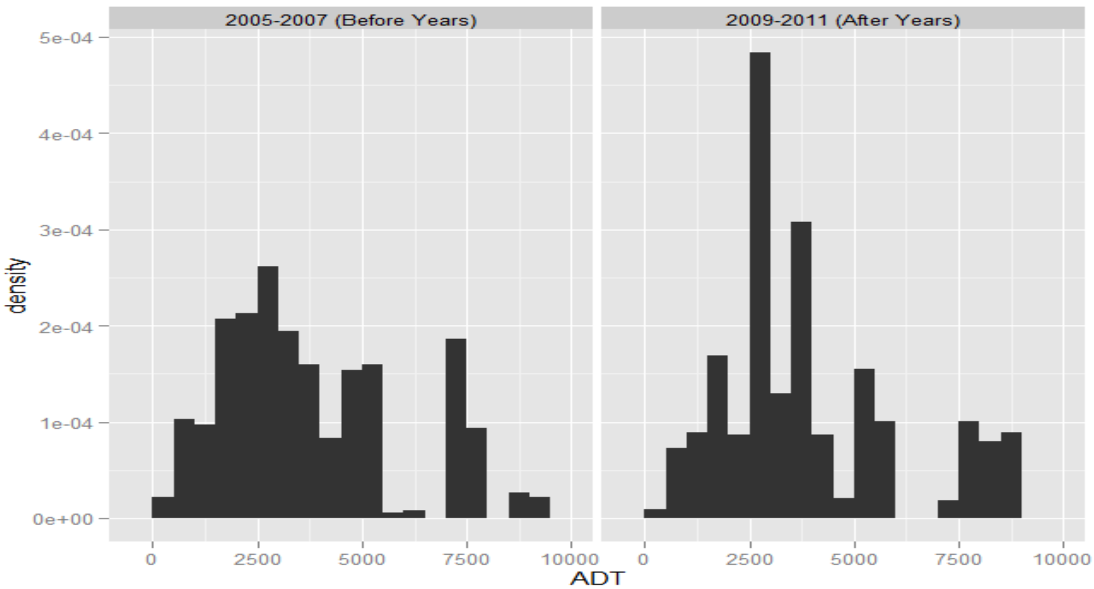

Figure 1
Density of AADT in before-after periods

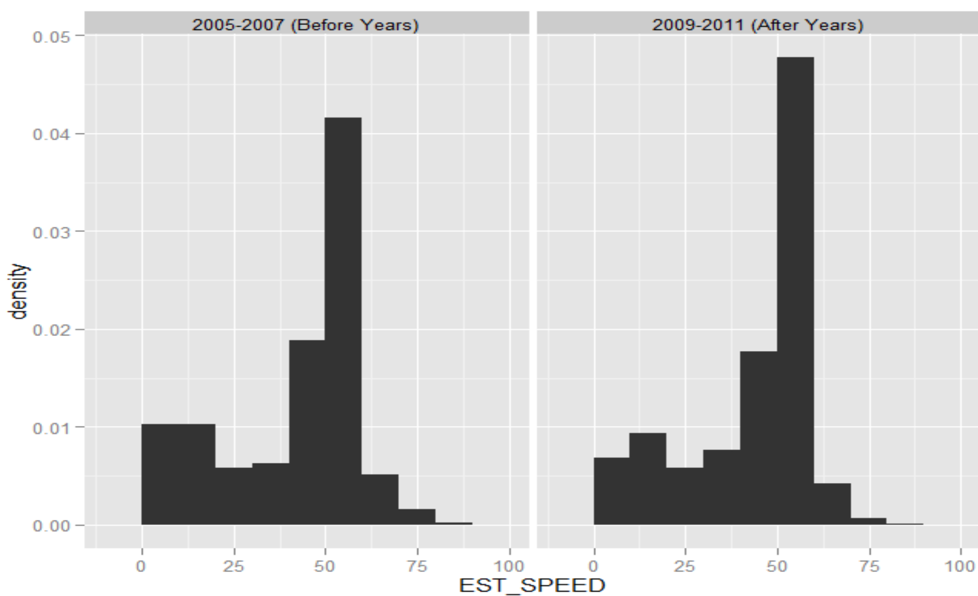

Figure 2
Density of estimated speed of the vehicles involved in crashes in before-after periods

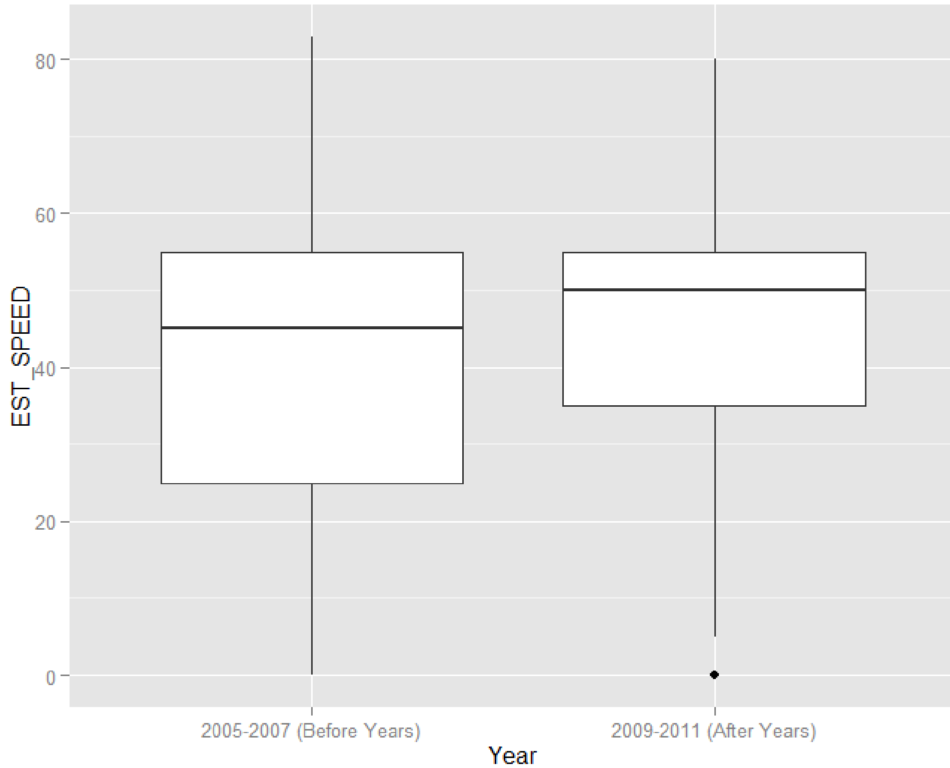

Figure 3
Box and whisker plot of estimated speed of the vehicles involved in crashes in before-after periods

Figure 4 plots the relationship between crash rate and AADT for the two study periods. Under same or similar AADT, crash rates were generally higher in the before periods than the after periods.

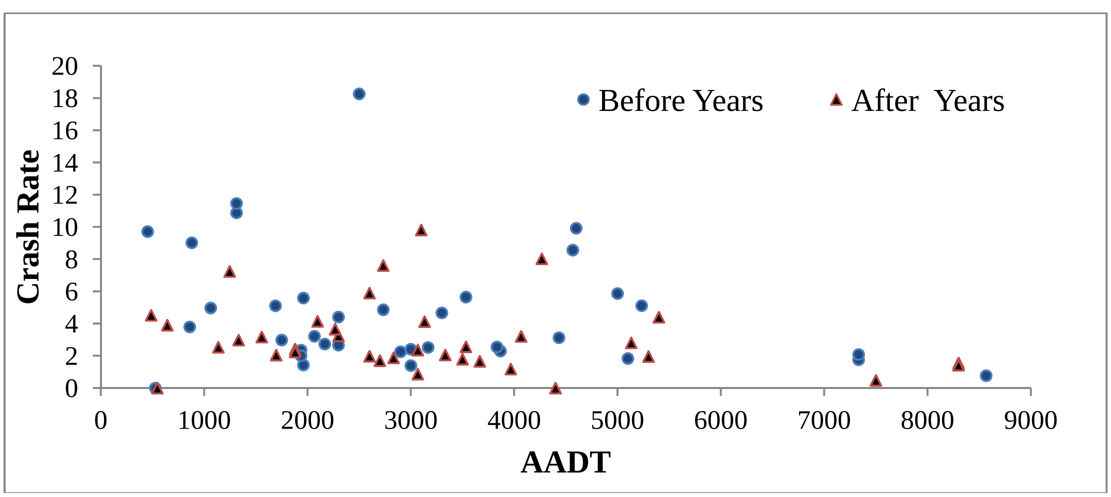

Figure 4
AADT vs. crash rate in before-after periods

Crash Characteristics

In addition to the change in traffic characteristics, researchers also investigated the change in crash characteristics. Figure 5 shows the crash severities by year.

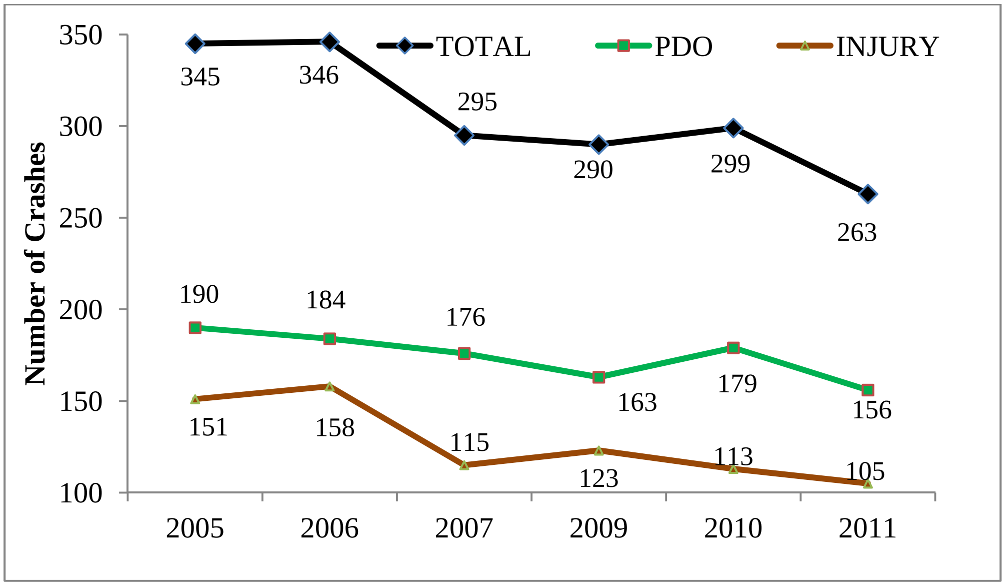

Figure 5
Crash severity in before-after periods

There is a slight increase in the fatalities mainly due to a high number in 2010 as shown in Table 10.

Table 10
Fatal crashes in before and after years

Severity Type	2005	2006	2007	2009	2010	2011
Fatal crashes	4	4	4	4	7	2

The occurrence of a fatal crash is an extremely rare event considering the magnitude of AADT. Annual fatal crashes are highly random. Therefore, the increase in 2010 could be a variation from the mean. The injury crashes in the after period decreased by 19.6% and Property Damage Only (PDO) crashes decreased by 9.5%.

It is always interesting to see the changes in type of collisions in the before and after periods. Figure 6 gives the changes in types of collision during before and after periods. Single vehicle crashes are seen as the most significant type of collisions.

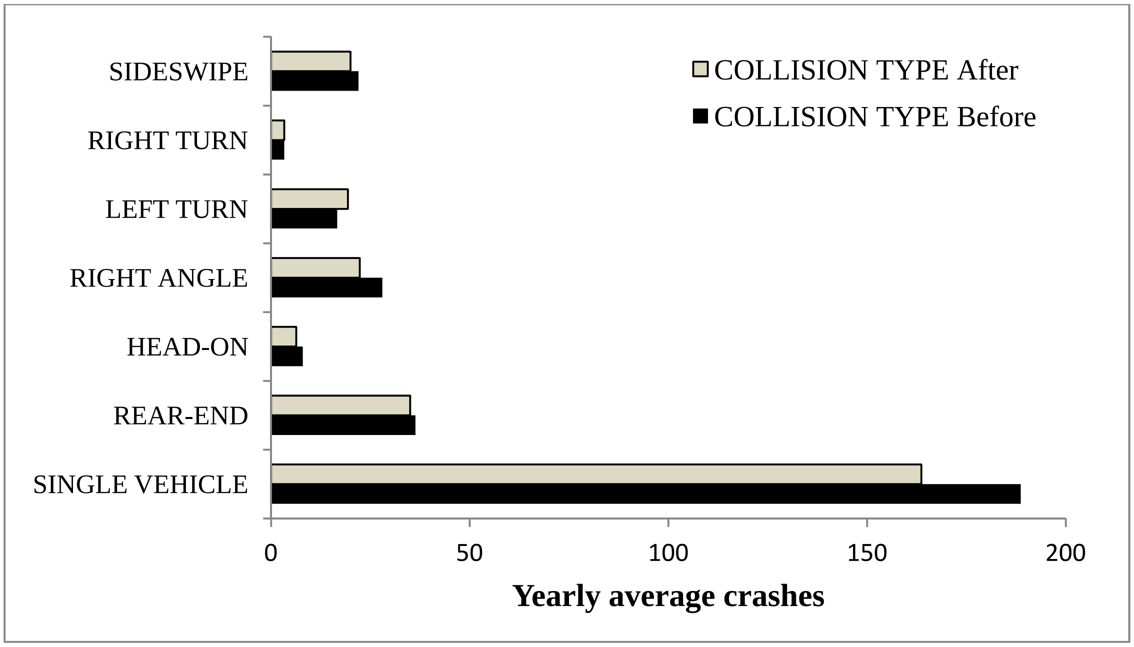

Figure 6
Crash severity in before-after periods—by type

Clearly, single vehicle crashes reduced after the edge line installation. These crashes are commonly involved in road departures. Overall, single vehicle crashes decreased by 13%, rear-end crashes decreased by 4%, and right angle crashes decreased by 20% in the after time period. On the other hand, left-turn crashes increased by 16%. The crash data also shows that the road departure crashes reduced nearly by 17% in the after period which clearly specifies the positive safety impact of edge line markings.

Figure 7 shows a density plot of crash hour in the before-after period of edge line installation. Minor changes in the night-time crashes are visible from this plot.

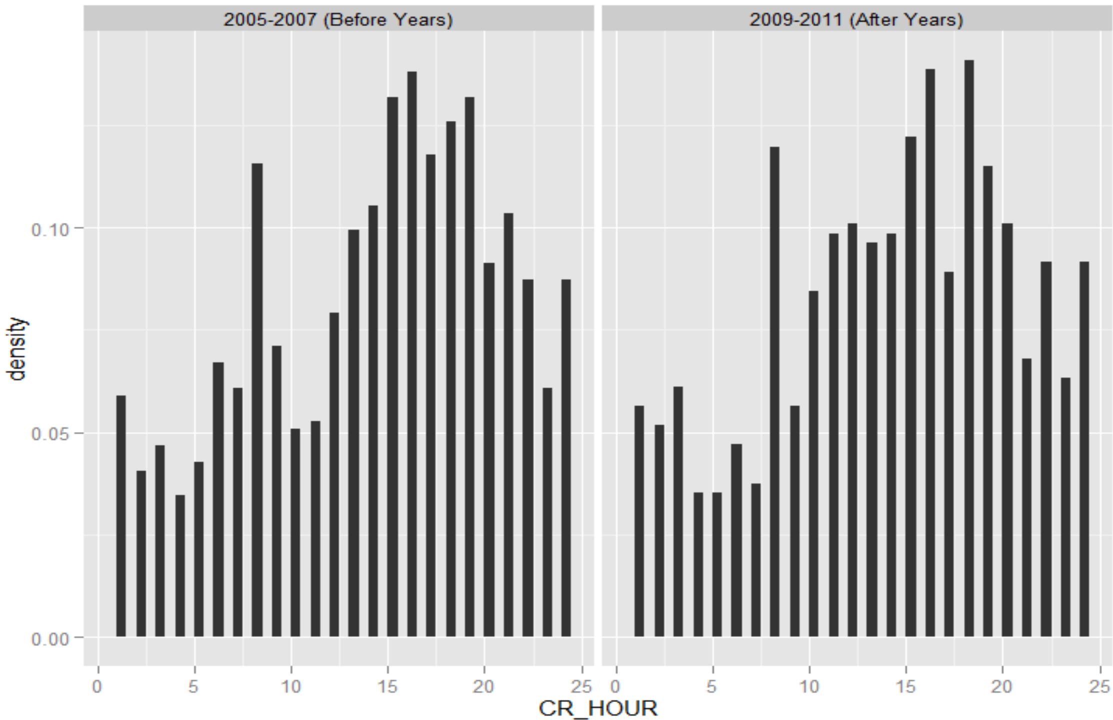

Figure 7
Density plot of crash hour in before-after periods

Table 11 lists the number of crashes under different lighting conditions. The majority of crashes happened in daylight. As shown in Table 11, daylight crashes decreased by 14% and night time crashes (with no street light) decreased by 12%. But crashes under the proper lighting condition seemed to increase. The number of crashes increased by 16% for roadway segments with the proper lighting. The higher operating speed caused by behavioral adaptation in a more visible zone may have affected this result.

Table 11
Lighting condition for before and after years

	2005	2006	2007	2009	2010	2011
DAYLIGHT	203	211	169	174	168	157
DARK - NO STREET LIGHTS	114	117	103	93	113	88
DARK - CONTINUOUS STREET LIGHT	7	6	6	9	4	9
DARK - STREET LIGHT AT INTERSECTION ONLY	7	1	2	5	5	3

Figure 8 represents the crash scenario based on the surface condition. Under wet and dry surface conditions, fewer crashes were seen during the after years. When pavement is wet, edge line markings are not as clearly visible as under dry conditions. The negligible decrease in wet pavement surface justifies this criterion (14.90% decrease in dry condition and 8.20% decrease in wet condition).

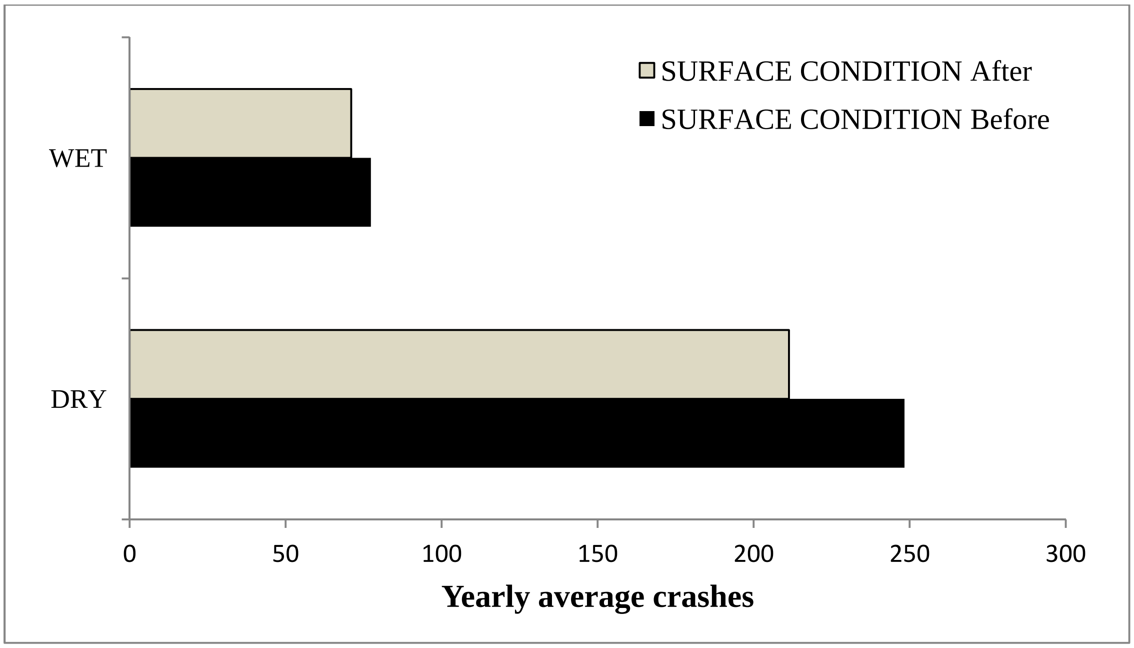

Figure 8
Surface condition in before-after years

Driver Characteristics

Human factor is considered as a practical, scientific discipline that tries to enhance the relationship between devices and systems and the user. The main focal point of this discipline in highway safety is the roadway user. Driving errors such as wrong perceptions, slower reactions, and poor decision making are the products of a poor match between the needs and capabilities of drivers and the task demands on the roadway. To link driver, vehicle, roadway, and environmental factors to specific criteria of driver behavior and performance is the important task to improve overall road safety. Driver related factors can be divided into four broad categories: background factors (experience, training, profession, etc.); demographic factors (age, gender, license state, etc.); physiological factors (driving behavior, physical and mental health, vision, hearing, etc.); and social factors (life quality, social health, etc.). The behaviors of drivers depend on these factors. The driving task like speed and headway selection, lane maintenance, lane changing varies with different driver profiles (normal, aggressive, distracted, impaired, drowsy, reckless, cautious, etc.). About 52% of Louisiana's license holders are female. Although males were involved in more crashes, they were also engaged in more vehicle miles travelled. The breakdown of the crashes by male and female offenders over the period of investigation is shown in Figure 9. It is seen that female involvement in crashes does not change much after the installation of edge lines. In the crash database, about 5% of the records have no driver gender information, which explains why the sum of "male" and "female" crashes doesn't add up to the total number of crashes.

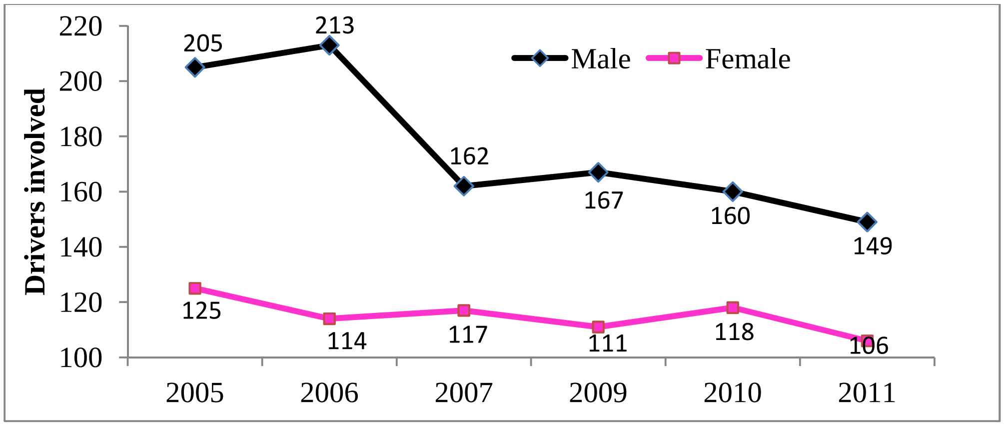

Figure 9
Male and female drivers in traffic crashes

It is well known that drivers in different age groups behave differently. The very young and the very old have the highest crash rates but for different reasons. To see the effect of edge lines by age group, the crash frequency was divided by age group as youths (15-24), middle-aged drivers (25-54), and seniors (55 and above). The middle-aged groups were subdivided into 10-year age groups (25-34, 35-44, and 45-54). The distribution of crashes based on driver's age was plotted in Figure 10. Young drivers (15-24) were seen to be involved in fewer crashes after the placement of edge lines. Although it is not surprising to see small variations between the before and after periods due to the regression-to-the-mean effect, the 17% drop in the age group 15-24 was engrossing. On the other hand, crashes increased in age group 55-64 by 8%.

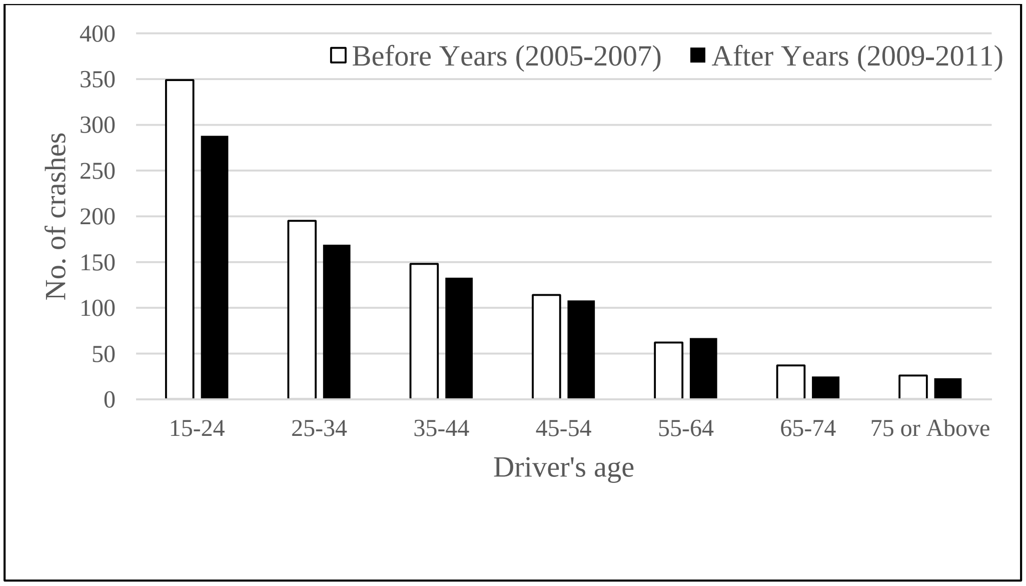

Figure 10
Driver age distribution

Figure 11 and Figure 12 show the impact of driver distraction and violation in traffic crashes in the selected segments in before and after years. Over the last 20 years, the concept of driver distraction has been considered as a key focus in the field of human factor related research. A large and expanding body of research has documented the myriad ways in which distraction can impact on driving performance and safety. Edge line installation indicates a reduction in the number of crashes caused by distracted and violation driving. The possible reason is the edge line markings help the drivers in daylight or in dark to maintain their proper guided way.

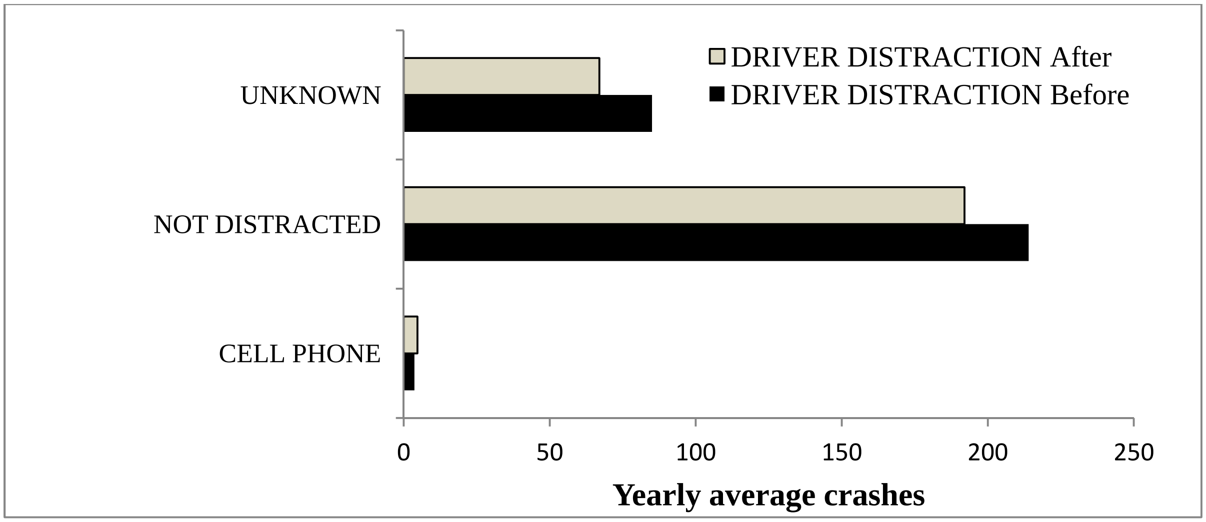

Figure 11
Driver distraction related crashes in before and after period

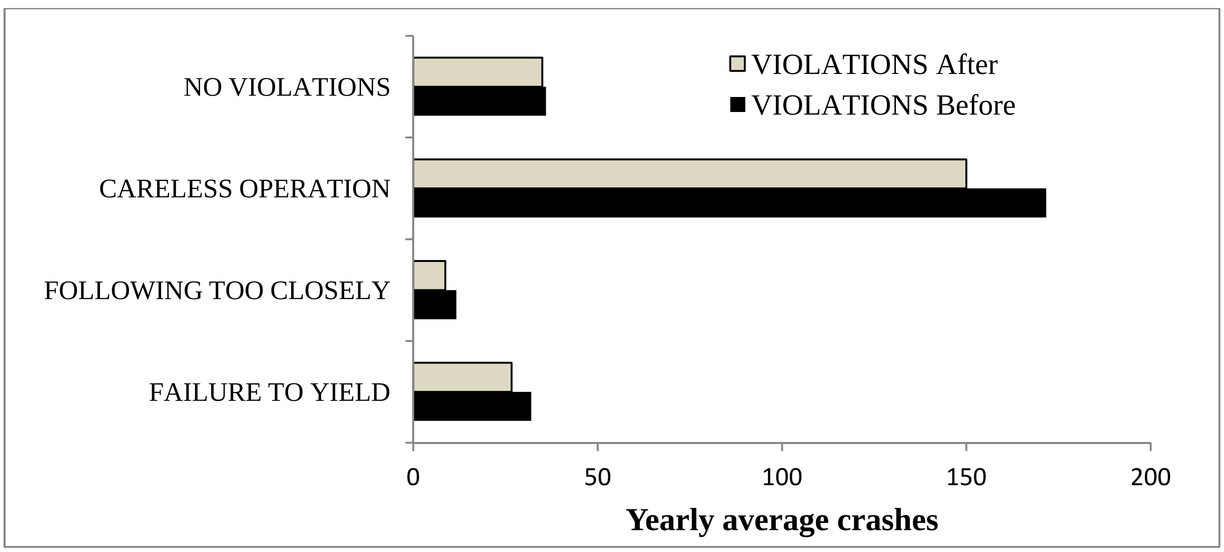

Figure 12
Driver violation induced crashes in before and after period

Correlation between Contributing Factors

Various categorical and numerical variables were considered for analysis in this study. A complete list of the analyzed variables is given in Appendix A. The challenge was to select the appropriate variables for observing the impact of edge line markings in rural two-lane highways. The significant variables investigated in this section are: AADT, driver's age, posted speed, estimated speed, and crash hour. Estimated driving speed (driver's operating speed) and crash hour are considered as two important numerical variables because of their significant impact on the safety outcome of edge line markings. Figures 13-17 provide information on the relationship between the association factors. In these figures, it is important to note that any missing value against any particular crash number doesn't generate data points. Figure 13 illustrates the distribution of operating speed by crash severity and crash hour for the before and after time periods.

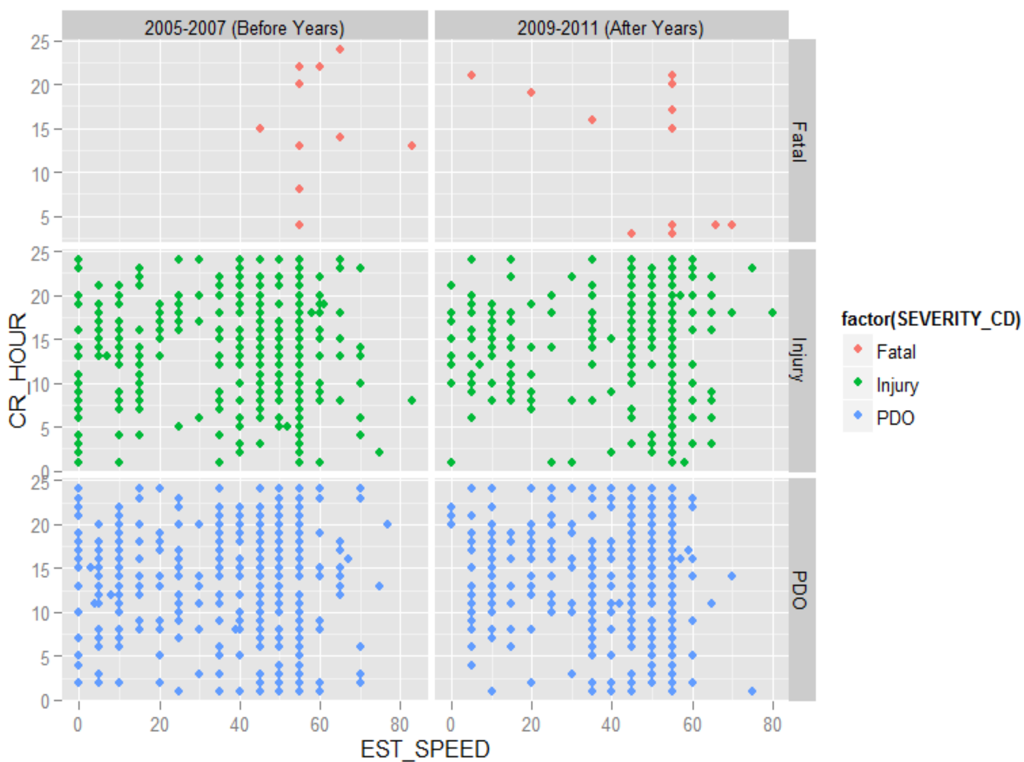

Figure 13
Correlation between crash hour and estimated speed with crash severity

It is a close correlation between crash hour and estimated operating speed in fatal crashes. The higher speed is the key reason for the crash occurrence during the before period. In after years, two fatal crashes were seen to have occurred under lower speed at night. For injury and PDO crashes, high speed driving has higher concentration of crash occurrences.

Figure 14 shows the correlation between crash hour and estimated operating speed in comparison with weather condition. The figure indicates that a higher speed is the significant factor for crash incidents in cloudy and rainy weather. Figure 15 shows the correlation between crash hour and estimated speed in comparison with driver's license state. Most crashes are associated with the local license holders while the non-local drivers are seen to be involved in crashes when the operating speed is higher in before years. A closer look at the fatal crashes in before-after period, it was seen that non-Louisiana drivers in before periods were involved in fatal crashes when the operating speed was higher.

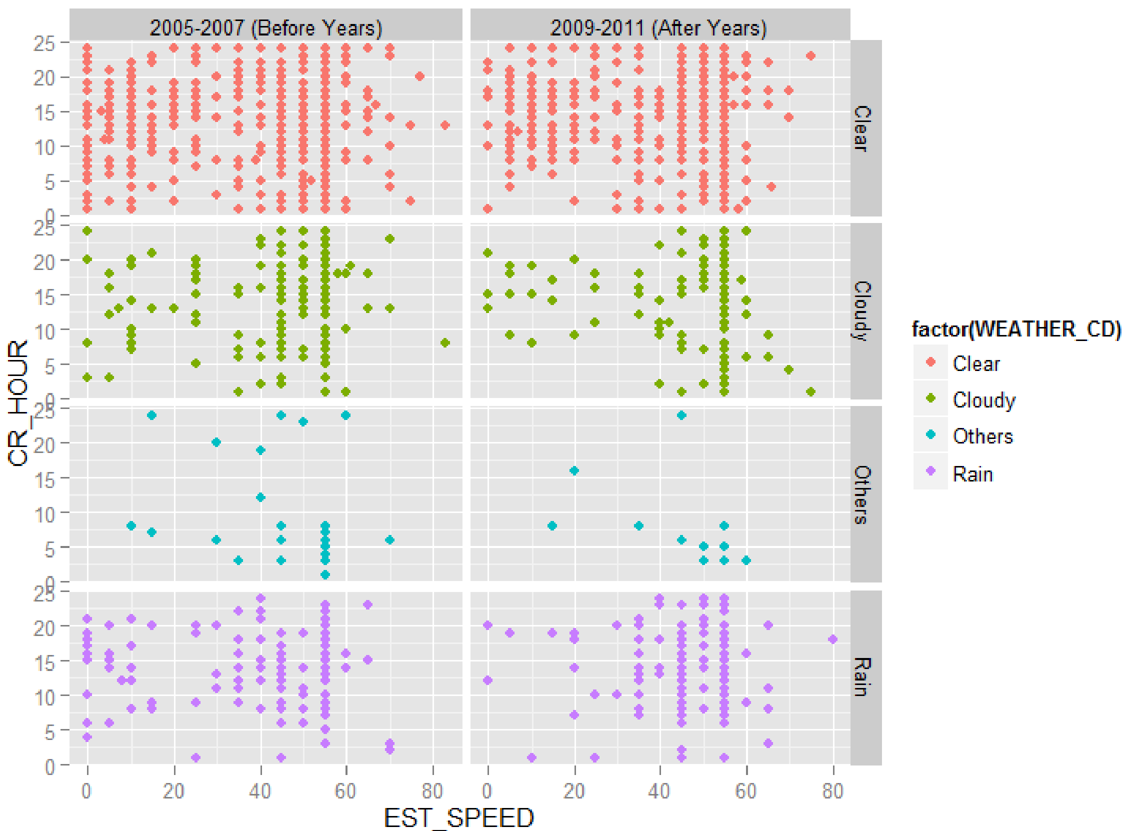

Figure 14
Correlation between crash hour and estimated speed with weather condition

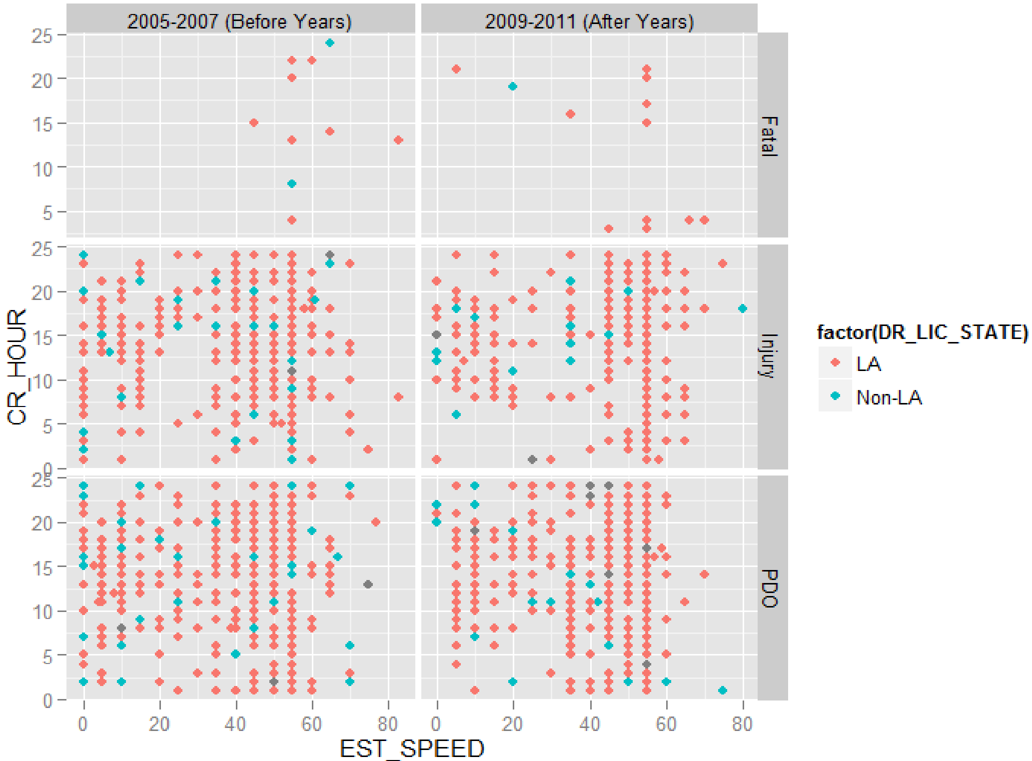

Figure 15
Correlation between crash hour and estimated speed with driver's license state

Both alcohol and drug impaired drivers are more likely to cause a fatal or severe injury crash than sober drivers. Alcohol is more often involved in rural-area crashes than in urban-area crashes. In 2011, alcohol was involved in 45% of rural and in 34% of urban fatal crashes in Louisiana. Figure 16 and Figure 17 shows the relationship between impaired driving speed and crash occurrence hours. Impaired drivers are seen to be involved in more fatal or injury crashes when the operating speed is higher in both before and after years. From the figures, it can be inferred that edge line installation has little effect on the lane-keeping tendency for the impaired drivers, which resulted in traffic crashes.

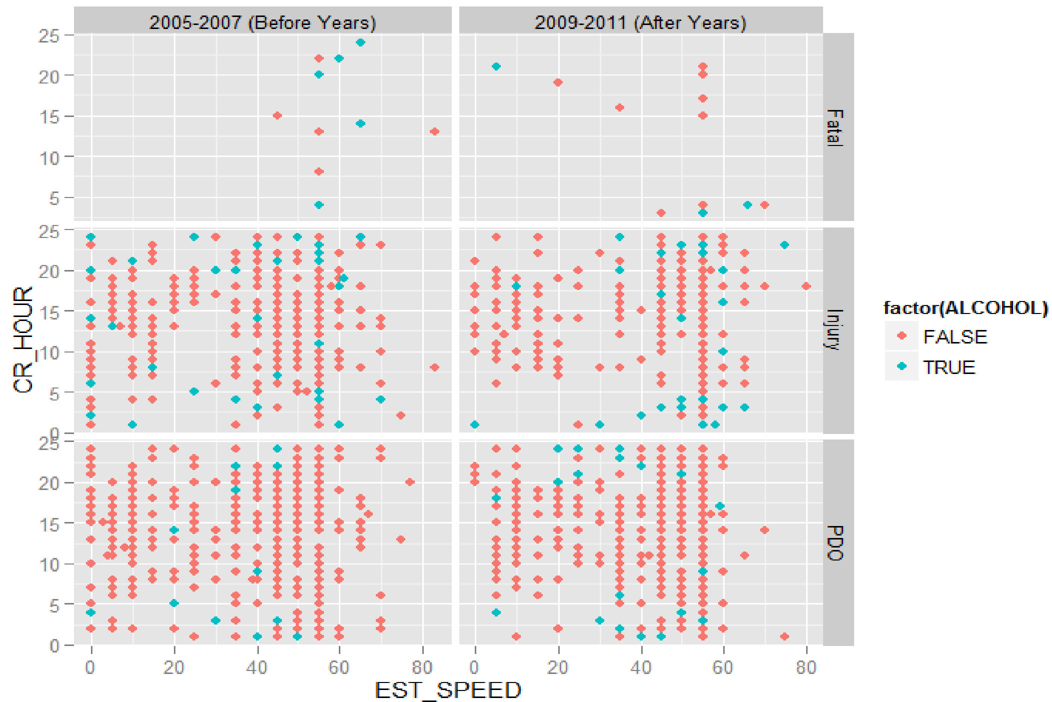

Figure 16
Correlation between crash hour and estimated speed with alcohol related crashes

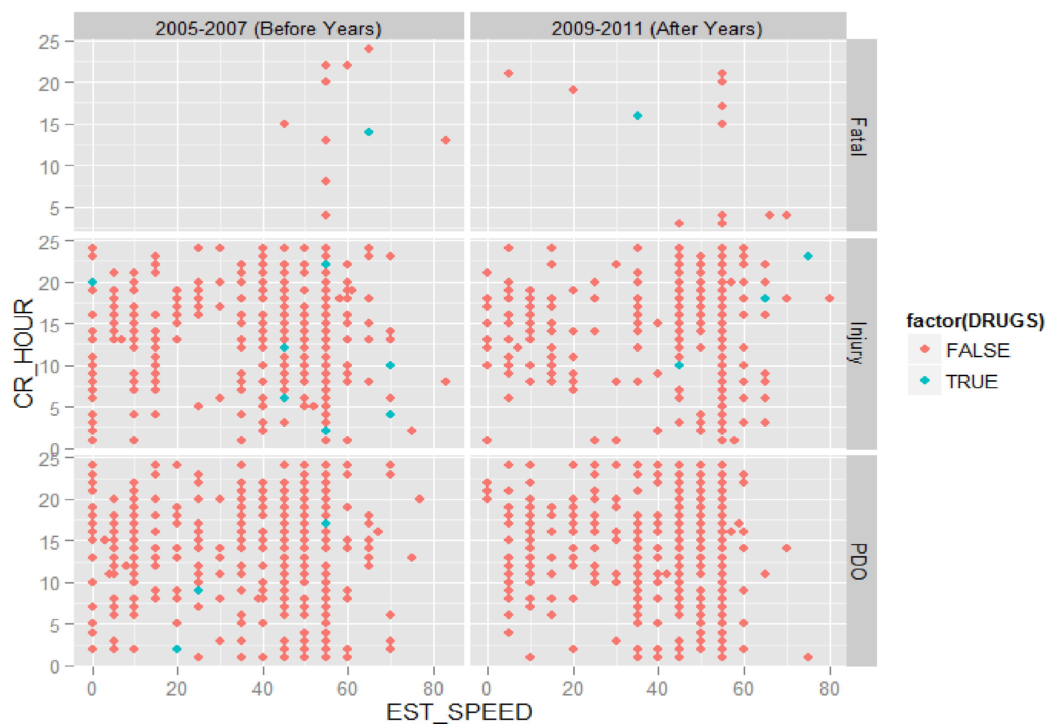

Figure 17
Correlation between crash hour and estimated speed with drugs related crashes

DISCUSSIONS OF RESULTS

Positive Safety Trend

Although the results show a decline in crashes, the overall crash reduction trend in the last few years should be considered, excluding the year 2011. For the past several years, Louisiana along with the entire country has been experiencing a steady decline in annual crash frequencies. The total traffic fatalities in the United States has declined from 42,708 in 2006 to 41,259, 37,423, 33,808 and 32,788 in 2007, 2008, 2009 and 2010, respectively *[22]*.In 2011, Louisiana experienced 630 fatal crashes (decreased by 2.02% from 2010), 677 persons killed (decreased by 5.97% from 2010), 43,343 injury traffic crashes (increased by 2.06% from 2010)*[23]*. As illustrated in Table 12, the number of crashes in Louisiana has also decreased since 2006 except 2011. During the study period, the total crashes reduced by 5.6% from the before years (2005-2007) to the after years (2009-2011).

Table 12
Total crashes by year

Year	Total Crashes	Percentage Change
2005	158,474	
2006	162,190	2.34% (increase)
2007	159,400	1.72% (decrease)
2008	157,420	1.24% (decrease)
2009	155,829	1.01% (decrease)
2010	147,643	5.25% (decrease)
2011	149,629	1.35% (increase)
2005-2007 (total)	480,064	
2009-2011 (total)	453,101	5.62% (decrease)

Table 13 summarizes the results from both of the methods. Two columns are shown in the table to evaluate the confidence interval. By observing the results, it is seen that all of the districts experienced a positive safety impact from edge line installation except District 03. The Empirical Bayes results show tighter values than the improved prediction in most of the districts.

Table 13
Crash modification factor with confidence interval

			Improved prediction method			Empirical Bayes method		
DOTD District	Section Length	No. of Control Sections	$\hat{\theta}$	$\hat{\theta} + 3 * sd(\hat{\theta})$	$\hat{\theta} - 3 * sd(\hat{\theta})$	$\hat{\theta}$	$\hat{\theta} + 3 * sd(\hat{\theta})$	$\hat{\theta} - 3 * sd(\hat{\theta})$
02	1.38	1	0.37	0.88	-0.13	0.45	1.04	-0.15
03	31.96	9	1.09	1.44	0.73	1.13	1.45	0.82
04	6.06	2	0.53	0.96	0.10	0.56	0.99	0.12
05	24.75	4	1.00	1.31	0.68	0.99	1.26	0.73
07	12.51	2	0.65	1.05	0.24	0.74	1.17	0.30
08	4.84	2	0.7	1.20	0.20	0.72	1.20	0.22
58	1.17	1	0.71	1.66	-0.24	0.71	1.65	-0.22
61	7.85	3	0.53	0.83	0.23	0.54	0.82	0.25
62	19.12	4	0.64	0.85	0.43	0.66	0.85	0.48
All	**109.64**	**28**	**0.83**	**1.00**	**0.65**	**0.84**	**0.95**	**0.72**

The crash reduction is also investigated by the pavement width of a rural two-lane highway as shown in Table 14.

Table 14
Decreasing trend of crashes on rural two-lane highways

Year	Less than 20'	Less than 22' and bigger than or equal to 20'	22'	More than 22'	Total
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 (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 (2009-2011)	226	2,791	2,947	6,570	12,534
Change	19.58%	-1.27%	0.37%	-7.53%	-4.01%

According to the crash record, the crash reduction is nearly 4.01% for rural two-lane highways of all pavement widths and is 1.3% for narrow highways (less than 22 ft. and bigger than or equal to 20 ft.) during the study period. Most of the studied control sections were in the "less than 22 ft. and wider than or equal to 20 ft." group. For the safety trend analysis, the safety improvement of this group was calculated. Considering this fact, the estimated crash modification factor would be estimated as 0.85 (0.84+0.01) with a standard deviation 0.039. That means the range of the CMF is {0.73, 0.96}.

Benefit-Cost Analysis

The cost for installing 6-in. waterborne edge lines varies based on the agency rate and product. According to the Louisiana estimates, the average cost for a fatal cost is $4,376,304, for an injury crash is $137,670, and for a PDO is $3,292. Installing edge lines reduces injury and PDO crashes, thus the average cost of crashes would be considered as a safety benefit. The observed reduction of crashes is considered here for the benefit-cost analysis. One fatal crash increase in after years is excluded from the calculation because the number of annual fatal crashes is highly random with a small sample size. The estimated benefit-cost ratio for edge line installation ranges from 18.89 to 117.53 per lane mile based on agency rate and material. The benefit-cost estimations are shown in Table 15.

Table 15
Estimated benefit-cost ratio for edge line installation

	Fatal Crash	**Injury Crash**	**PDO**
Crash Reduction	-1	83	52
Cost including loss of quality of life	4,376,304	137,670	3,292
Savings from averted crashes		11,426,610	171,184
Total Benefit	11,597,794		
	Paint (DOTD)	**Paint (Contractor)**	**Thermoplastic (Contractor)**
Cost per lane mile	$450	$700	$2800
Total cost	$98,676	$153,496	$613,984
Benefit-cost ratio	117.53	75.56	18.89

CONCLUSIONS

Based on the analysis results and discussion, the following conclusions can be drawn:

1. Placing pavement edge lines on rural two-lane highways in Louisiana can not only change vehicle lateral positions but can also reduce crashes.
2. Based on the Empirical Bayes method, the most reliable CMF for edge lines on narrow, rural two-lane highways (pavement width less than 22 ft. and wider than or equal to 20 ft.) is 0.84.
3. Considering the safety trend in Louisiana, the final estimated CMF is 0.85, which means there is a 15% expected crash reduction in edge line with implementation on narrow, rural two-lane highways. The statistically estimated standard deviation for the CMF is 0.039.
4. The CMF range (0.73, 0.96) indicates a certainty in crash reduction with edge lines.
5. The crash reduction is consistent in all crash types and is particularly significant in single vehicle crashes. Most of single vehicle crashes are ROR crashes.
6. The benefits overwhelmingly offset the cost with edge line implementation. The most conservative estimation for benefit and cost ratio is 19.

RECOMMENDATIONS

This project recommends the use of edge lines on narrow, rural two-lane highways whenever financially and operationally feasible. Since each DOTD district bears the responsibility of implementing pavement markings, DOTD may want to establish a policy asking each district to implement edge lines if sufficient resources are available. Under financial or operational constraints, roadways with higher traffic volumes should have priority to have edge lines implemented.

ACRONYMS, ABBREVIATIONS, AND SYMBOLS

AADT	Annual Average Daily Traffic
ADT	Average Daily Traffic
AASHTO	American Association of State Highway and Transportation Officials
CMF	Crash Modification Factor
CRF	Crash Reduction Factor
DOT	Department of Transportation
EB	Empirical Bayes
FHWA	Federal Highway Administration
HSM	Highway Safety Manual
ITS	Intelligent Transportation Systems
DOTD	Department of Transportation and Development
LTRC	Louisiana Transportation Research Center
MUTCD	Manual of Uniform Traffic Control Devices
NCHRP	National Cooperative Highway Research Program
OD	Opposite Direction
PDO	Property Damage Only
ROR	Run-off Road
RPM	Raised Pavement Marker
SHSP	Strategic Highway Safety Plan
SPF	Safety Performance Function
VMT	Vehicle Mile Traveled
VPD	Vehicles Per Day

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APPENDIX A

Table 16
The variables considered for analysis of before-after study

Geometric Variables	Driver Variables	Crash Variables	Vehicle Variables
MEDIAN_WIDTH	VEH_NUM	CR_HOUR	VEH_YEAR
NUM_LANES	DR_AGE	DAY_OF_WK	VEH_COND_CD
PAVEMENT_TYPE	ALCOHOL	SEVERITY_CD	VEH_LIGHTING_CD
PAVEMENT_WIDTH	DRUGS	MAN_COLL_CD	
SURF_COND_CD	DR_COND_CD	NUM_VEH	
ALIGNMENT_CD	DR_DISTRACT_CD	PRI_CONTRIB_FAC_CD	
HWY_TYPE_CD	DR_INJ_CD	LIGHTING_CD	
TRAFF_CNTL_CD	DR_LIC_NUM	WEATHER_CD	
TRAFF_CNTL_COND_CD	DR_LIC_STATE		
ROAD_COND_CD	DR_SEX		
ROAD_TYPE_CD	EST_SPEED		
INTERSECTION	VIOLATIONS_CD		
ADT			
FUNCTIONAL_CLASS			
HIGHWAY_CLASS			
MEDIAN_WIDTH			
POSTED_SPEED			

APPENDIX B

Calculation Details for Before-After Study

Table 17
Crash data with AADT values for before and after periods

					2005		2006		2007		2009		2010		2011	
Control Section	Logmile From	Logmile To	District	Length	Total Crash	AADT	Total Crash	AADT	Total Crash	AADT	Total Crash	AADT	Total Crash	AADT	Total Crash	AADT
845-02	0	1.38	02	1.38	4	830	4	830	3	980	0	1020	1	1460	6	1520
823-27	0	1.89	03	1.89	12	2100	8	2400	2	2400	7	1380	3	1310	9	3600
392-01	0.54	1.45	03	0.91	5	1290	6	1400	3	1250	2	1300	4	1210	2	1230
820-29	0	5.85	03	5.85	5	1930	5	1950	7	2000	10	2100	12	2800	12	2900
820-29	5.85	7.1	03	1.25	6	1930	7	1950	1	2000	7	2100	8	2800	6	2900
857-25	0	0.6	03	0.6	0	1930	1	1940	1	1940	2	1930	0	1940	0	1770
857-25	0.6	9.04	03	8.44	11	1930	10	1940	15	1940	9	1930	19	1940	11	1770
389-01	2.59	7.15	03	4.56	13	8700	11	9200	9	7800	8	7300	8	7600	1	7600
204-03	1.97	5.12	03	3.15	7	1810	5	1770	7	1670	3	1670	6	1710	4	1710
056-05	0	0.24	03	0.24	4	4700	3	4800	6	4300	3	4400	3	4200	3	4200
801-09	0.61	4	03	3.39	11	4000	10	4100	11	3500	25	3700	12	2900	12	2800
210-04	3.67	5.35	03	1.68	12	3800	2	3900	5	3800	5	4000	10	4100	8	4100
048-02	4.72	8.29	04	3.57	9	2200	10	2300	6	2400	9	2600	4	2700	4	2800
079-01	2.95	5.44	04	2.49	3	420	6	460	2	480	3	460	1	480	2	520
158-01	3.1	5.41	05	2.31	9	2100	4	2200	2	2200	4	2300	6	2200	10	2300
158-01	5.45	10.19	05	4.74	20	2800	23	2700	25	2700	37	2800	39	2700	33	2700
837-08	0	7.19	05	7.19	7	3000	8	3000	18	3000	8	3200	9	3000	3	3000
837-08	7.19	9.46	05	2.27	7	3000	7	3000	4	3000	4	3200	7	3000	7	3000

					2005		2006		2007		2009		2010		2011	
Control Section	Logmile From	Logmile To	District	Length	Total Crash	AADT	Total Crash	AADT	Total Crash	AADT	Total Crash	AADT	Total Crash	AADT	Total Crash	AADT
156-02	0.3	6.58	05	6.28	19	2800	13	2900	14	3000	20	3600	16	3800	6	3600
156-01	0	1.96	05	1.96	22	4900	19	5100	22	5000	17	5100	22	5500	13	5600
066-05	2.58	4.18	07	1.6	7	3300	14	3300	5	3300	2	3400	6	3500	4	3100
189-01	0	10.91	07	10.91	14	860	16	880	9	840	8	680	8	590	13	660
835-09	0	0.04	08	0.04	0	510	1	520	0	550	0	560	0	540	0	540
147-04	0.63	5.43	08	4.8	16	3900	11	2900	14	2700	9	3500	14	3500	10	3500
068-04	18.71	19.88	58	1.17	5	3200	3	5900	4	6200	2	3900	4	4000	1	4000
219-05	0.39	4.51	61	4.12	11	2200	11	2000	8	2000	8	2900	6	3000	10	2600
847-04	0	1.51	61	1.51	12	3600	15	3500	6	3500	5	3500	6	3500	3	3600
227-03	0	2.22	61	2.22	9	1720	10	1670	3	1680	2	1570	3	1560	7	1540
281-04	1.85	5.8	62	3.95	14	4200	25	4500	22	4600	23	5100	14	5300	8	5500
281-04	5.8	11.5	62	5.7	15	1070	9	1070	10	1050	5	1100	8	1140	6	1170
853-27	0.34	2.04	62	1.7	9	7100	15	7300	1	7600	11	7900	8	8400	5	8600
853-27	2.04	8.3	62	6.26	33	7100	35	7300	36	7600	23	7900	26	8400	33	8600
270-02	0	0.18	62	0.18	5	2300	4	2600	0	2600	0	3000	3	3000	2	3300
848-07	0.67	2	62	1.33	9	5000	15	5300	14	5400	9	5300	3	5400	9	4700

Table 18
Table for improved prediction calculation

					Before Years		After Years									
Control Section	Logmile From	Logmile To	District	Length	Total Crash	AADT	Total Crash	AADT	$r_{d(j)}$	$r_{tf(j)}$	$r_{tf(j)}*r_{d(j)}*K_{(j)}$	$r_{d(j)}^2*K_{(j)}$	$r_{d(j)}^2*K_{(j)}^2$	Before v^2	After v^2	$var(r_{tf})$
845-02	0	1.38	02	1.38	11	880	7	1333	1.00	1.52	17	11	121	0.0098	0.0065	0.0376
823-27	0	1.89	03	1.89	22	2300	19	2097	1.00	0.91	20	22	484	0.0042	0.0045	0.0072
392-01	0.54	1.45	03	0.91	14	1313	8	1247	1.00	0.95	13	14	196	0.0066	0.0070	0.0122
820-29	0	5.85	03	5.85	17	1960	34	2600	1.00	1.33	23	17	289	0.0047	0.0038	0.0150
820-29	5.85	7.1	03	1.25	14	1960	21	2600	1.00	1.33	19	14	196	0.0047	0.0038	0.0150
857-25	0	0.6	03	0.6	2	1937	2	1880	1.00	0.97	2	2	4	0.0048	0.0049	0.0091
857-25	0.6	9.04	03	8.44	36	1937	39	1880	1.00	0.97	35	36	1296	0.0048	0.0049	0.0091
389-01	2.59	7.15	03	4.56	33	8567	17	7500	1.00	0.88	29	33	1089	0.0021	0.0022	0.0033
204-03	1.97	5.12	03	3.15	19	1750	13	1697	1.00	0.97	18	19	361	0.0052	0.0053	0.0098
056-05	0	0.24	03	0.24	13	4600	9	4267	1.00	0.93	12	13	169	0.0027	0.0028	0.0048
801-09	0.61	4	03	3.39	32	3867	49	3133	1.00	0.81	26	32	1024	0.0030	0.0034	0.0042
210-04	3.67	5.35	03	1.68	19	3833	23	4067	1.00	1.06	20	19	361	0.0030	0.0029	0.0066
048-02	4.72	8.29	04	3.57	25	2300	17	2700	1.00	1.17	29	25	625	0.0042	0.0037	0.0109
079-01	2.95	5.44	04	2.49	11	453	6	487	1.00	1.07	12	11	121	0.0211	0.0193	0.0465
158-01	3.1	5.41	05	2.31	15	2167	20	2267	1.00	1.05	16	15	225	0.0044	0.0042	0.0094
158-01	5.45	10.19	05	4.74	68	2733	109	2733	1.00	1.00	68	68	4624	0.0037	0.0037	0.0074
837-08	0	7.19	05	7.19	33	3000	20	3067	1.00	1.02	34	33	1089	0.0035	0.0034	0.0072
837-08	7.19	9.46	05	2.27	18	3000	18	3067	1.00	1.02	18	18	324	0.0035	0.0034	0.0072
156-02	0.3	6.58	05	6.28	46	2900	42	3667	1.00	1.26	58	46	2116	0.0035	0.0031	0.0106
156-01	0	1.96	05	1.96	63	5000	52	5400	1.00	1.08	68	63	3969	0.0026	0.0025	0.0059
066-05	2.58	4.18	07	1.6	26	3300	12	3333	1.00	1.01	26	26	676	0.0033	0.0032	0.0066
189-01	0	10.91	07	10.91	39	860	29	643	1.00	0.75	29	39	1521	0.0101	0.0139	0.0134
835-09	0	0.04	08	0.04	1	527	0	547	1.00	1.04	1	1	1	0.0175	0.0168	0.0370
147-04	0.63	5.43	08	4.8	41	3167	33	3500	1.00	1.11	45	41	1681	0.0034	0.0032	0.0079
068-04	18.71	19.88	58	1.17	12	5100	7	3967	1.00	0.78	9	12	144	0.0026	0.0029	0.0033
219-05	0.39	4.51	61	4.12	30	2067	24	2833	1.00	1.37	41	30	900	0.0045	0.0036	0.0153

					Before Years		After Years									
Control Section	Logmile From	Logmile To	District	Length	Total Crash	AADT	Total Crash	AADT	$r_{d(j)}$	$r_{tf(j)}$	$r_{tf(j)}*r_{d(j)}*K_{(j)}$	$r_{d(j)}{}^2*K_{(j)}$	$r_{d(j)}{}^2*K_{(j)}{}^2$	Before v^2	After v^2	$var(r_{tf})$
847-04	0	1.51	61	1.51	33	3533	14	3533	1.00	1.00	33	33	1089	0.0031	0.0031	0.0063
227-03	0	2.22	61	2.22	22	1690	12	1557	1.00	0.92	20	22	484	0.0053	0.0057	0.0093
281-04	1.85	5.8	62	3.95	61	4433	45	5300	1.00	1.20	73	61	3721	0.0028	0.0025	0.0076
281-04	5.8	11.5	62	5.7	34	1063	19	1137	1.00	1.07	36	34	1156	0.0081	0.0076	0.0180
853-27	0.34	2.04	62	1.7	25	7333	24	8300	1.00	1.13	28	25	625	0.0022	0.0021	0.0055
853-27	2.04	8.3	62	6.26	104	7333	82	8300	1.00	1.13	118	104	10816	0.0022	0.0021	0.0055
270-02	0	0.18	62	0.18	9	2500	5	3100	1.00	1.24	11	9	81	0.0039	0.0034	0.0113
848-07	0.67	2	62	1.33	38	5233	21	5133	1.00	0.98	37	38	1444	0.0025	0.0026	0.0049

<u>Calculation Details</u>

$$\hat{\lambda} = L = 852,\ V\hat{A}R(\hat{\lambda}) = L = 852, K = 986$$

$$r_d = \frac{After\ Years}{Before\ Years} = \frac{3}{3} = 1, r_{tf} = \frac{\hat{A}_{avg}}{\hat{B}_{avg}} = \frac{108870}{104597} = 1.041,\ \hat{\pi} = r_d \hat{r}_{tf} K = 1024$$

$$v = 1 + \frac{7.7}{number\ of\ count-days} + \frac{1650}{AADT^{0.82}}$$

$$v^2(\hat{A}_{avg}) = (1 + \frac{7.7}{3} + \frac{1650}{108870^{0.82}})^2 \times 10^{-4} = 0.00136,\ v^2(\hat{B}_{avg}) = (1 + \frac{7.7}{3} + \frac{1650}{104597^{0.82}})^2 \times 10^{-4} = 0.00136$$

$$V\hat{A}R(\hat{r}_{tf}) = (\hat{r}_{tf})^2[v^2(\hat{A}_{avg}) + v^2(\hat{B}_{avg})] = 0.0029,\ V\hat{A}R(\hat{\pi}) = (r_d)^2[(\hat{r}_{tf})^2 K + K^2 V\hat{A}R(\hat{r}_{tf})] = 3887.88$$

$$\hat{\delta} = \hat{\pi} - \hat{\lambda} = 174,\ V\hat{A}R(\hat{\delta}) = V\hat{A}R(\hat{\pi}) + V\hat{A}R(\hat{\lambda}) = 4739.88,\ \hat{\sigma}(\hat{\delta}) = 68.84$$

$$\hat{\theta} = (\hat{\lambda}/\hat{\pi})/[1 + V\hat{A}R\{\hat{\pi}\}/\hat{\pi}^2] = 0.83$$

$$V\hat{A}R(\hat{\theta}) = \frac{\theta^2[(V\hat{A}R(\hat{\lambda})/\lambda^2) + (V\hat{A}R(\hat{\pi})/\pi^2)]}{[1 + (V\hat{A}R(\hat{\pi})/\pi^2)]^2}] = 0.0033,\ \hat{\sigma}(\hat{\theta}) = 0.0575$$

Table 19
Table for Empirical Bayes method

					Before Years		After Years										
Control Section	Logmile From	Logmile To	District	Length	Total Crash	AADT	Total Crash	AADT	Estim. Before	Estim. After	k	w	M_i	$Var(M_i)$	c_i	π_i	$Var(\pi_i)$
845-02	0	1.38	02	1.38	11	880	7	1333	0.97	1.47	0.171	0.149	9.50	8.08	1.52	14.40	18.55
823-27	0	1.89	03	1.89	22	2300	19	2097	3.48	3.18	0.125	0.035	21.36	20.62	0.91	19.47	17.14
392-01	0.54	1.45	03	0.91	14	1313	8	1247	0.96	0.91	0.259	0.213	11.22	8.83	0.95	10.65	7.96
820-29	0	5.85	03	5.85	17	1960	34	2600	9.19	12.19	0.040	0.004	16.97	16.89	1.33	22.51	29.72
820-29	5.85	7.1	03	1.25	14	1960	21	2600	1.96	2.60	0.189	0.088	12.94	11.81	1.33	17.17	20.78
857-25	0	0.6	03	0.6	2	1937	2	1880	0.93	0.90	0.393	0.297	1.68	1.18	0.97	1.63	1.11
857-25	0.6	9.04	03	8.44	36	1937	39	1880	13.10	12.72	0.028	0.002	35.95	35.87	0.97	34.90	33.81
389-01	2.59	7.15	03	4.56	33	8567	17	7500	31.31	27.41	0.052	0.002	33.00	32.94	0.88	28.89	25.25
204-03	1.97	5.12	03	3.15	19	1750	13	1697	4.42	4.28	0.075	0.017	18.76	18.44	0.97	18.19	17.34
056-05	0	0.24	03	0.24	13	4600	9	4267	0.88	0.82	0.983	0.526	6.62	3.14	0.93	6.14	2.70
801-09	0.61	4	03	3.39	32	3867	49	3133	10.51	8.51	0.070	0.007	31.86	31.65	0.81	25.82	20.78
210-04	3.67	5.35	03	1.68	19	3833	23	4067	5.16	5.48	0.140	0.026	18.63	18.14	1.06	19.77	20.42
048-02	4.72	8.29	04	3.57	25	2300	17	2700	6.58	7.73	0.066	0.010	24.82	24.57	1.17	29.13	33.86
079-01	2.95	5.44	04	2.49	11	453	6	487	0.90	0.97	0.095	0.095	10.04	9.09	1.07	10.78	10.48
158-01	3.1	5.41	05	2.31	15	2167	20	2267	4.01	4.20	0.102	0.025	14.73	14.36	1.05	15.41	15.72
158-01	5.45	10.19	05	4.74	68	2733	109	2733	10.38	10.38	0.050	0.005	67.73	67.40	1.00	67.73	67.40
837-08	0	7.19	05	7.19	33	3000	20	3067	17.29	17.67	0.033	0.002	32.97	32.91	1.02	33.70	34.39
837-08	7.19	9.46	05	2.27	18	3000	18	3067	5.46	5.58	0.104	0.019	17.77	17.43	1.02	18.16	18.22
156-02	0.3	6.58	05	6.28	46	2900	42	3667	14.60	18.46	0.038	0.003	45.92	45.80	1.26	58.06	73.22
156-01	0	1.96	05	1.96	63	5000	52	5400	7.85	8.48	0.120	0.015	62.17	61.23	1.08	67.14	71.42
066-05	2.58	4.18	07	1.6	26	3300	12	3333	4.23	4.27	0.148	0.034	25.27	24.42	1.01	25.52	24.91
189-01	0	10.91	07	10.91	39	860	29	643	7.52	5.63	0.022	0.003	38.91	38.80	0.75	29.11	21.71
835-09	0	0.04	08	0.04	1	527	0	547	0.02	0.02	5.900	0.997	0.02	0.00	1.04	0.02	0.00
147-04	0.63	5.43	08	4.8	41	3167	33	3500	12.18	13.47	0.049	0.004	40.88	40.72	1.11	45.19	49.74
068-04	18.71	19.88	58	1.17	12	5100	7	3967	4.78	3.72	0.202	0.040	11.71	11.23	0.78	9.11	6.80
219-05	0.39	4.51	61	4.12	30	2067	24	2833	6.82	9.36	0.057	0.008	29.81	29.56	1.37	40.86	55.56

					Before Years		After Years										
Control Section	Logmile From	Logmile To	District	Length	Total Crash	AADT	Total Crash	AADT	Estim. Before	Estim. After	k	w	M_i	$Var(M_i)$	c_i	π_i	$Var(\pi_i)$
847-04	0	1.51	61	1.51	33	3533	14	3533	4.28	4.28	0.156	0.035	31.99	30.86	1.00	31.99	30.86
227-03	0	2.22	61	2.22	22	1690	12	1557	3.01	2.77	0.106	0.034	21.35	20.62	0.92	19.67	17.50
281-04	1.85	5.8	62	3.95	61	4433	45	5300	14.04	16.78	0.060	0.004	60.80	60.54	1.20	72.69	86.53
281-04	5.8	11.5	62	5.7	34	1063	19	1137	4.86	5.19	0.041	0.008	33.75	33.47	1.07	36.08	38.24
853-27	0.34	2.04	62	1.7	25	7333	24	8300	9.99	11.31	0.139	0.014	24.79	24.45	1.13	28.06	31.33
853-27	2.04	8.3	62	6.26	104	7333	82	8300	36.80	41.65	0.038	0.001	103.93	103.82	1.13	117.63	133.00
270-02	0	0.18	62	0.18	9	2500	5	3100	0.36	0.45	1.311	0.784	2.22	0.48	1.24	2.76	0.74
848-07	0.67	2	62	1.33	38	5233	21	5133	5.58	5.47	0.177	0.031	37.00	35.86	0.98	36.29	34.50

Calculation Details

For each of the control section, predicted crashes in the before years would be calculated by the SPF formula,

$$P_i = \sum_{y=1}^{y_{0i}-1} \hat{E}(k_{iy}) = 266$$

$$k = \frac{0.236}{L}, \quad w_i = \frac{1}{1+\frac{P_i}{k}},$$

$$M_i = w_i P_i + (1-w_i)K = 958, \; Var(M_i) = (1-w_i)M_i$$

For each of the control section, predicted crashes in the after years would be calculated by SPF formula,

$$P_i = \sum_{y=y_{0i}+1}^{y} \hat{E}(k_{iy}) = 279$$

$$C_i = \frac{\sum_{y=y_{Oi}+1}^{y} \hat{E}(k_{iy})}{\sum_{y=1}^{y=y_{Oi}-1} \hat{E}(k_{iy})} = \frac{Q_i}{P_i}$$

$$\hat{\pi}_i = C_i M_i, \qquad V\hat{a}r(\pi_i) = C_i^{\,2} V\hat{a}r(M_i) = C_i^{\,2}(1-w_i)M_i$$

$$\hat{\pi} = \sum_{i=1}^{I} \pi_i = 1016 \qquad V\hat{a}r(\hat{\pi}) = \sum_{i=1}^{I} Var(\hat{\pi}_i) = 1071.90$$

$$\hat{\theta} = \frac{L}{\hat{\pi}\left[1 + \frac{\hat{VAR}\{\hat{\pi}\}}{\hat{\pi}^2}\right]} = 0.84$$

$$\hat{\sigma}\{\hat{\theta}\} = \frac{\hat{\theta}\sqrt{\left(\frac{1}{L} + \frac{\hat{Var}\{\hat{\pi}\}}{\hat{\pi}^2}\right)}}{1 + \frac{\hat{Var}\{\hat{\pi}\}}{\hat{\pi}^2}} = 0.039$$