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Louisiana Transportation Research Center

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ABSTRACT

The Louisiana Strategic Highway Safety Plan is to reach the goal of Destination Zero Death on Louisiana roadways. This tall order calls for all feasible crash countermeasures to be implemented. A great number of crash countermeasures have been identified by various representative documents such as PART IV of the Highway Safety Manual, Countermeasures that Work from the National Highway Transportation Safety Administration, and the Crash Modification Factor (CMF) Clearinghouse *[1-3]*. However, crash countermeasures unique to Louisiana have not been thoroughly evaluated before.

After reviewing and documenting crash countermeasures as well as their CMFs, the research team developed two CMFs that are unique in Louisiana. The first is for converting four-lane urban undivided roadways to five-lane. Undivided multilane roadways have consistently exhibited low safety performance, particularly in urban or suburban areas where roadside development is relatively intense. Changing a four-lane undivided road to a divided roadway by either building a boulevard cross-section or installing a physical barrier is a desirable option to improve the safety performance, but it requires significant resources and sometimes a strong political will. The state traffic engineers have re-striped several segments of urban undivided four-lane roadways to a five-lane roadway with two-way-left-turn-lane (TWLTL) by re-striping pavement markings without increasing pavement width in three Louisiana Department of Transportation and Development (DOTD) districts. Although the five-lane roadway is no longer an acceptable roadway type for new construction in Louisiana, the impressive crash reductions on both roadway segments clearly demonstrate it as a feasible solution under financial constrained conditions. Based on the statistical analysis with six years of crash data (three years before and three years after excluding the project implementation year), the CMFs for all roadways are estimated to be less than 0.6 with a standard deviation less than 0.07.

The second CMF developed is for raised pavement markers (RPM) and striping. Raised pavement markers are intended as safety devices on roadways. Intuitively, convinced by its safety benefits, DOTD has been using RPM for many years on all freeways in the state. This project evaluates the safety benefit of RPM along with pavement striping on freeways with nine years of data. The analysis results from three methods indicate that RPM has significant benefit in reducing nighttime crashes on rural freeways and there are no safety benefits on urban freeways.

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IMPLEMENTATION STATEMENT

The main objective of this project is the development of two crash modification factors (CMF) that can be used for the safety management system in selecting and evaluating crash countermeasures. Considering the huge B/C ratio from the lane-converting (re-striping), DOTD should implement this crash countermeasure on all urban undivided roadways under the current tight budgetary situation. A safety evaluation study on all undivided urban roadways is recommended before the implementation.

The project results also showed that the state should continue the current practice of inspecting and maintaining raised pavement markers on all Louisiana rural freeways.

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INTRODUCTION

Approximately 700 people lose their lives and 50,000 are injured each year in traffic crashes on Louisiana's roadways. Traffic crashes cost the citizens of Louisiana $6.03 billion dollars each year, which accounts for about 4.5% of personal income and $2,104 for every licensed driver in Louisiana *[4]*. In 2006 Louisiana traffic fatality rate (fatalities per 100 million VMT) was 2.2, while the national average was 1.41; the lowest rate was 0.78, in Massachusetts. Although Louisiana has made great strides in reducing the number of crashes, particularly fatal crashes, in recent years, our fatal crash rate of 1.56 is still higher than the national average of 1.10, as shown in Figure 1.

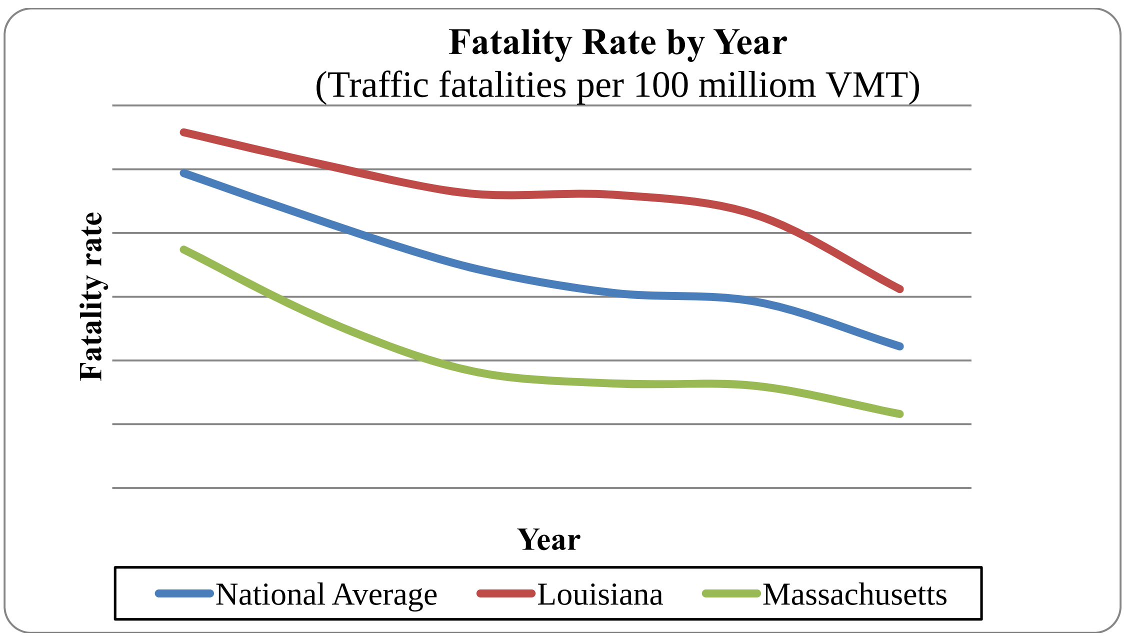

Figure 1
Highway fatality rate by year *[5]*

To improve highway safety, DOTD has developed a Louisiana Strategic Highway Safety Plan (SHSP) aimed at reducing fatal and severe injury crashes on Louisiana roadways. The goal of Louisiana SHSP is to reach Destination Zero Deaths on Louisiana roadways, which calls to cut the fatalities by half by 2030, as shown in Figure 2 *[6]*.

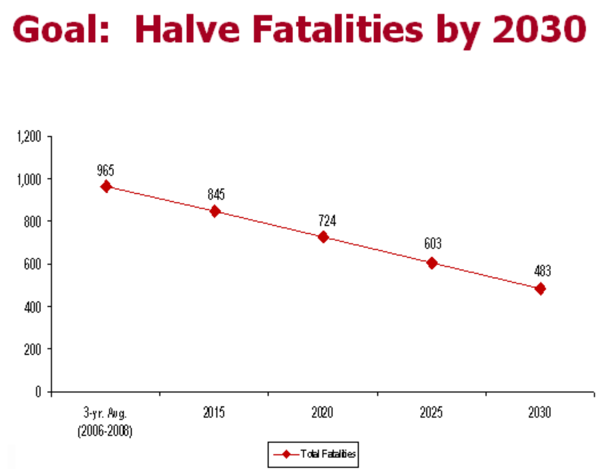

Figure 2

Goal of Louisiana Strategic Highway Safety plan *[7]*

To reach such a hefty goal, a list of actions is proposed, aiming to reduce crashes and crash severities in all 4E aspects (engineering, education, enforcement, and emergency service). Developing Louisiana crash reduction factors is one task proposed by the SHSP. A crash reduction factor is a multiplicative factor used to compute the expected number of crashes after implementing a given crash countermeasure at a specific site. Crash reduction factors (CRF) have been used to identify and prioritize the most effective safety improvement measures. The estimated economic benefits depend on the expected crash reductions from each countermeasure. Many states use CRF as a tool to evaluate the cost-benefit relationships between various roadway improvements and their effectiveness in reducing crashes and/or reducing the severity of those crashes. DOTD is currently using CRFs developed by FHWA, titled "Desktop Reference for Crash Reduction Factors" dated September 2007 *[8]*.

As has been long recognized, the effectiveness of a crash countermeasure may vary from state to state because of the differences in road-user behavior and travel environment, as well as the quality and sources of research used to determine CRF. Not all CRF listed in the FHWA desktop references are clearly related to particular situations in Louisiana. There is a need to compile and present crash countermeasures in a way that would make it easier for DOTD engineers and planners to apply CRF for a given situation.

OBJECTIVE

The primary goal of this research was to develop and document a list of CRFs to be used by DOTD. Particularly, this research will:

- Document the state-of-the-practice in CRF development.
- Develop inexpensive CRFs for Louisiana with available information.

SCOPE

This project aims to develop crash modification factors that are unique to Louisiana. Only highway related CMFs are considered here (excluding crash countermeasures for vehicles and human factors). The analysis will only focus on the data from Louisiana highways.

METHODOLOGY

As outlined in the proposal, this study consists of the following major steps:

1. CRF overview and crash countermeasures catalog
2. Development of Louisiana crash modification factors

Crash Reduction Factor Overview and Crash Countermeasures Catalog

The crash reduction factor is the percentage of crash reduction that might be expected after implementation of a crash countermeasure. Expected countermeasure effectiveness is also commonly expressed as a CMF, which, introduced in the first edition of Highway Safety Manual (HSM), serves the same purpose *[1]*. Mathematically, crash reduction factor equals to one minus crash modification factor. For example, a CRF of 0.2 implies a CMF of 0.8. A CMF is a multiplicative factor used to compute the expected number of crashes after implementing a given countermeasure at a specific site. A CMF greater than 1.0 indicates an expected increase in crashes, while a value less than 1.0 indicates an expected reduction in crashes after implementation of a given countermeasure. For example, a CMF of 0.8 indicates an expected safety benefit; specifically, a 20% expected reduction in crashes. A CMF of 1.2 indicates an expected degradation in safety; specifically, a 20% expected increase in crashes. To account for the stochastic nature of crashes, standard deviation (standard error) is also used to measure the certainty of the estimated CMF.

Both CRFs and CMFs are commonly used in the field of traffic safety due to their straightforward application concept. To be consistent with the Highway Safety Manual (HSM), all future reference in this report uses CMF. Since highway safety is a complex system involving engineering, roadway user behavior, law/regulation and policy, vehicle design, and medical service, the 4E (engineering, education, enforcement, and emergency services) approach has been commonly recognized as a comprehensive way to reduce crashes. Thus, crash countermeasures could come from a variety of areas, categorized by the following:

- Roadway engineering
- Vehicle
- User behaviors
- Emergency services

According to the well-known Haddon Matrix devised by William Haddon in the 1970s, the occurrence and consequence of a crash depends on each of the above element conditions throughout the temporal aspect of the crash. As shown in Table 1, the matrix provides a conceptual framework to look at traffic crash systematically in order to develop the effective countermeasure to eliminate crashes and minimize the impact of a crash if it does occur.

Table 1
Illustration of Haddon Matrix

Phases	Roadway User (A)	Vehicle (B)	Travel Environment	
			Physical Environment (C)	**Socio-Economic Environment (D)**
Pre-Crash (1)	Physical and mental capacity compliance with traffic law	Speed, mass, and mechanical condition Crash avoidance design	Roadway features and weather condition	Public perception on protective gears and available funds for improving safety
Moment of Crash (2)	Protective gear Stature Posture	Crash Survivability design	Roadway features and degree of forgiveness design	Enforcement on traffic regulations and protective gears
Post-Crash (3)	Ability to report symptoms Age and physical conditions	Ease of access, fire risk	Emergency response time	Level of emergency and medical skills available to treating crash injuries

Thus, the category of crash countermeasure can be summarized in Table 2.

Table 2
Summary of potential crash countermeasures in all areas

Crash Countermeasure		Purpose	Targeted cells in the Matrix	Example
Roadway Design		Reduce crashes and severity of crashes by increase the safety and forgiveness of roadway facilities	1C, 2C	Forgiving roadside design to let lane-departure vehicle back to roadway
Traffic Control		Reduce crashes and severity of crashes by placing appropriate traffic control devices	1C, 2C	Positive guidance in pavement markings, signs and signals
User Behavior	**Voluntary**	Reduce crashes and severity of crashes by educating good, safety roadway user behaviors	1A	Driver education and safety public campaign
	Laws & Regulations	Reduce crashes and severity of crashes by establishing laws and regulation for required user behaviors	1D	Traffic laws
	Enforcement	Reduce crashes and severity of crashes by enforcing established traffic laws	1A	Enforcement programs
	Sanctions and treatment of Offenders	Reduce crashes and severity of crashes by punishing offenders	1A	Demerit point programs

The category of roadway engineering includes design and traffic control as well as the Intelligent Transportation Systems (ITS) actions that improve safety. Vehicles today are much safer than vehicles manufactured before. Vehicles of today are equipped with more crash avoidance features and designed to be more crashworthy. The review of crash countermeasure for vehicles is beyond scope of this study.

The available research on crash modification factors can be divided into two broader sections: (1) development of CMF for countermeasure(s), (2) review on the categorization and selection of available CMFs.

Research has been conducted on the development of CMFs during last 50 years. CMFs were first introduced in the Federal Hazard Elimination Program in the early 1980s *[9, 10]*. In the earlier approaches, CMFs were utilized to evaluate the safety impacts of any treatments in: (1) the geometry of a specific intersection or roadway segment, (2) the traffic control devices of the roadway segment or intersection, (3) the signalization condition of an intersection, and (4) the roadside clear zone *[11]*.

Different states and local safety agencies used numerous developed treatments in their efforts to decrease the number and severity of crashes at intersection and roadway segment locations. The National Cooperative Highway Research Program (NCHRP) started a project team (NCHRP Project 17-25) to develop an initial list of 78 important treatments, categorized as intersection-related, segment-related, ITS-related, other, and combined treatments. The findings were narrated in NCHRP Report 617 published in 2008 *[12]*. This list was based on treatments proposed in past safety guidance documents such as the NCHRP Report 500 guidelines. The HSM expands on the available CMFs found in NCHRP Report 617 to include lower and medium quality factors included in the report. Federal Highway Administration (FHWA) indicates that the HSM is projected to serve as a document that provides best practices rather than a policy, guideline or design manual that establishes requirements to be met by states. Shen et al. stated that about 80% of departments of transportation (DOTs) in the U.S. use CMF to improve crash-prone roadway safety which reflects FHWA intention *[13]*.

A major part of the HSM (Part D) is an all-inclusive list of CMFs, which is a compilation from past studies of the safety effects of various road treatments from the last five decades. The HSM used a very thorough inclusion/exclusion process to review the accuracy of the CMFs to determine their suitability for inclusion in the HSM. The literature review procedure, developed for the purpose of documenting it systematically, included the following major steps *[14]*.

Step 1. Determine estimate of safety effect of a treatment as per publication document;

Step 2. Adjust estimate of safety effect for potential bias from Regression-To-Mean (RTM) and changes in traffic volume;

Step 3. Determine ideal standard error of safety effect of the treatment;

Step 4. Apply method correction factor (MCF) to ideal standard error;

Step 5. Adjust corrected standard error to account for bias from RTM and changes in traffic volume; and

Step 6. Combine CMFs when specific criteria are met.

HSM listed three different sets of treatments based on the safety effectiveness:

1) Countermeasures with available CMFs
2) Countermeasures with known safety effects
3) Countermeasures with unknown safety effects

Table 3 shows the number of countermeasure listed in the HSM for these three categories:

Table 3
Total number of countermeasures listed in the HSM

Sec.	Name	No. of Countermeasures with available CMF	No. of Countermeasures with known safety effects	No. of Countermeasures with unknown safety effects
A	Roadway Segments	36	43	72
B	Intersections	24	27	84
C	Interchange	4	8	25
D	Special Facilities and Geometric Situations	5	16	68
E	Road Networks	3	16	5
	Total	72	110	254

Crash modification factors are typically developed through before-after studies of the used safety treatment. Three major before-and-after studies commonly used by the researchers are listed below-

1. The simple (naïve) before and after study
2. The before and after study with comparison group
3. The Empirical Bayes (EB) before and after study

CMFs can also be developed through cross-sectional studies. Research has also shown that the usage of the "simple before and after study" sometimes leads to biased values which tend to exaggerate the exact effectiveness of a countermeasure *[15, 16]*.

Recently, a web-based repository of CMFs named as the CMF Clearinghouse was established. The CMF Clearinghouse was established to provide transportation professionals*:*

- A regularly updated, online repository of CMFs,

- A mechanism for sharing newly developed CMFs, and
- Educational information on the proper application of CMFs *[3]*.

Development of Louisiana Crash Modification Factors

Developing unique CMFs for Louisiana is the main purpose of the project. Based on the investigation, two unique CMFs are generated for Louisiana in this study. The methods are discussed in the following sections:

Crash Modification Factor for Four-Lane to Five-Lane Urban Roadway Conversions

Undivided highways have consistently exhibited low safety performance, particularly in urban or suburban areas where driveway density is relatively high. While rural two lane highways experience the highest traffic fatality rate, undivided highways have the overall highest total crash rate (crashes per 100 million VMT) and crash injury rate (crash injuries per 100 million VMT) in the United States *[17]*. A high proportion of the crashes are rear-end collisions on this type of roadway. The undivided multilane roadway is a common type of roadway in both urban and rural areas. In Louisiana, there are about 1,200 miles of undivided multi-lane roadways (excluding two-lane roadways) and most of them are four-lane highways under the state Department of Transportation and Development System. Ninety-three percent of these roadways are in urban and suburban areas. Installing physical separation either by barrier or by green space (boulevard) has been the most recommended crash countermeasure for the problem. With sufficient roadway width, a four-lane undivided highway can also be easily changed to a five-lane roadway with the center lane for left-turns, which expectedly reduces rear-end collisions. This option, even though it is the least expensive one, is not considered as a good design option due to the access control problems. Louisiana has established policies discouraging five-lane roadway design in constructing new roads, and seldom considers it as an option in reducing crashes on undivided roadways. However, due to today's tight budget situation, the expensive solutions are out of reach. To meet the urgent need in crash reduction on this type of roadway, several district offices of DOTD converted undivided four-lane roadway to five-lane in the last decade.

South College Road, part of state route LA 3025, experienced the typical safety problems of undivided highways. It is located inside the city of Lafayette and is functioning as an arterial street. With an Annual Average Daily Traffic (AADT) around 28,000 in 2009, the majority of vehicles on the segment are through traffic. There are 14 major driveways connecting to business establishments, such as doctor offices and small residential areas. Three signalized intersections are located within this segment. The two signalized intersections in the middle of the segment are only 150 feet apart and their signal timing is designed in tandem, functioning as one signalized intersection, while the other one is a T-intersection with constant green light for eastbound through vehicles on South College and a ban on left-turns from the side street onto South College. The total length of this segment is 1.228 miles (on DOTD control section 828-23 from logmile 0.328 to 1.556). The crash rates computed as crashes per million vehicle-mile-traveled (VMT) for this roadway segment in the three years prior to the re-striping project were 8.49, 9.90 and 11.74, respectively. The high number of crashes on this road segment were a problem for some time.

In 2003, instead of waiting for available funds to implement the desirable solutions, the DOTD District 03 re-striped this segment of LA 3025, changing it from the four-lane undivided roadway to the five-lane roadway with continuous center lane for left-turning vehicles. The layout of the segment and lane configurations before and after the project is shown in Figure 3.

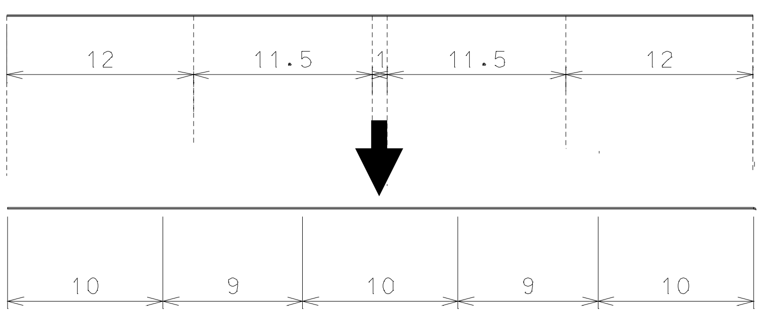

Figure 3
LA 3025 layout and lane configuration before and after the project (dimensions are in feet)

Encouraged by the significant crash reduction on South College Road three years after the re-striping project, District 03 office of DOTD applied the exact same measure in 2007 on LA 182 (on DOTD control section 032-02 between logmile 12.129 and 13.129). This one mile segment on LA 182 is located in Opelousas, a small city about 20 miles north of Lafayette. Passing through a suburban area with low population density, this segment is under a slightly different environment with AADT of 21,947 in 2009, about 22% smaller than the one on South College Road but with the same safety problems. There are 13 major driveways connecting to various businesses, such as small retail stores, fast food restaurants, gas stations, and residential areas. Three signalized intersections are located within this segment. The crash rates computed as crashes per million vehicle-mile-traveled (VMT) for this roadway segment in the three years prior to the re-striping project were 8.08, 9.69 and 6.62 respectively. The layout and lane configuration before and after period for the LA 182 segment is shown in Figure 4.

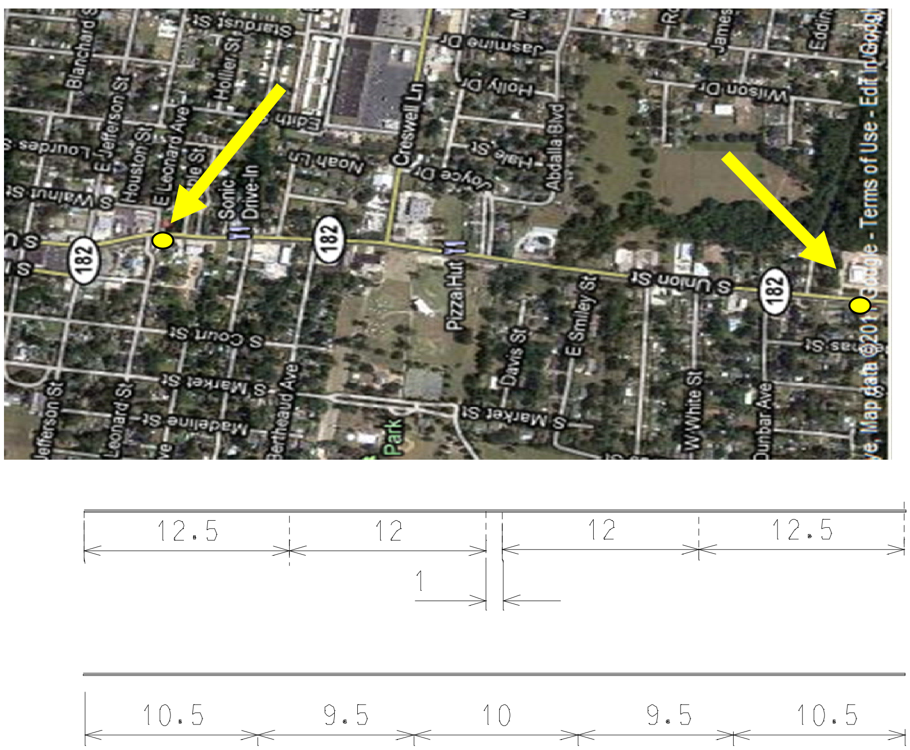

Figure 4
LA 182 layout and lane configuration before and after the project (dimensions are in feet)

The District 08 office also applied this solution on LA 28 (on DOTD control section 074-01 between logmile 0.14 and 1.06). The section is 0.92 mile long. It is situated in East in Pineville of Rapides Parish in Alexandria. Lying on the south bank of the Red River, this area is almost the exact geographic center of the Louisiana. The AADT between the before and the after time periods are very similar. Nearly 45 driveways are connected to various businesses such as fast food restaurants, gas stations, pharmacies, shopping centers, and residential areas. In 2005, this segment was re-striped from four-lane to five-lane. The layout and lane configuration before and after the re-striping project for the LA 28 segment is shown in Figure 5.

Figure 5
LA 28 layout and lane configuration before and after the project (dimensions are in feet)

The District 07 office of DOTD also applied 4U to 5T conversion on a segment of LA 1138 (control section 810-06 between logmile 2.78 and 3.85). The section is 1.07 miles long and is situated on West Prien Lake Road in Lake Charles. The segment starts at Lake St. and ends in Ryan St. In 1999, this segment was changed from a four-lane undivided to a five-lane roadway. There is a minor difference in AADT between before and after years. Nearly 50 driveways are connected to various businesses such as fast food shops, gas stations, pharmacies, shopping centers, electronics shops, car rentals, and residential areas. The layout before and after the re-striping project on this segment are shown in Figure 6.

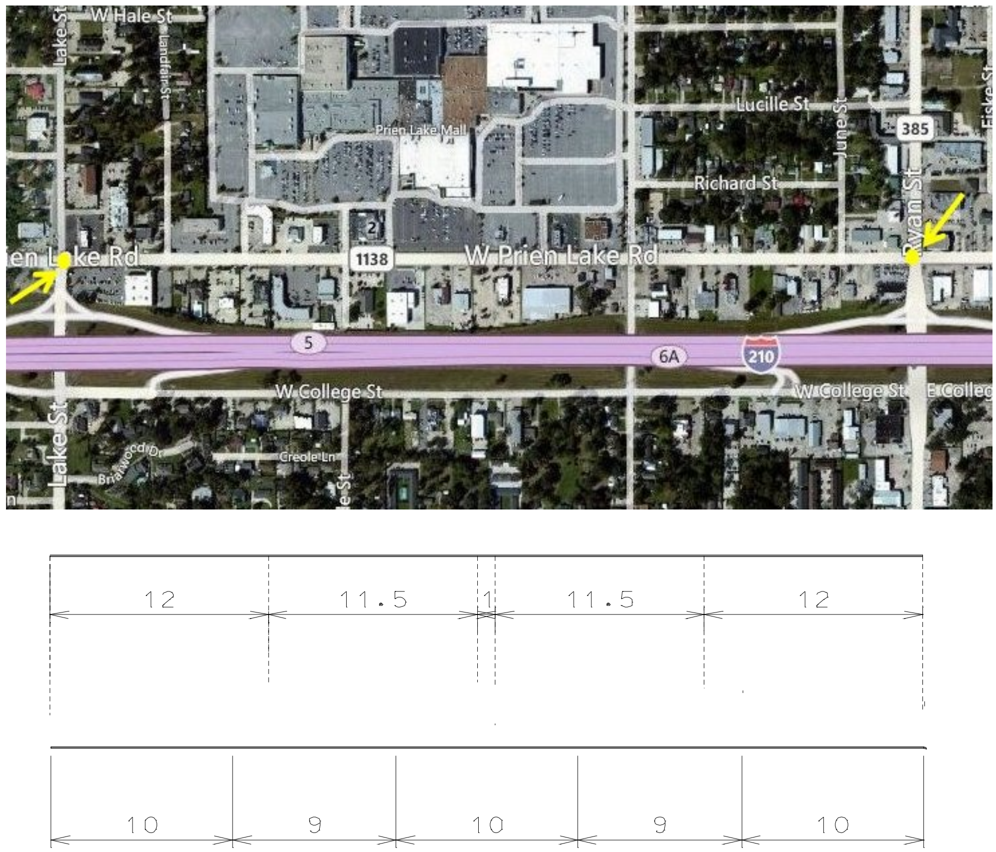

Figure 6
LA 1138 roadway layout before and after the project
(dimensions are in feet)

The number of crashes and crash rates before and after the re-striping projects for the above four segments are listed in Table 4. The speed limit remained the same on S. College road before and after the project implementation. However, the speed limit on the 0.44 miles of roadway on the south end of LA 182 segment (44%) was reduced from 50 mph to 45 mph after the re-striping project.

Table 4
Crash reduction summary

	Before		After		Percentage Change	
	Crashes	Average Crash Rate	Crashes	*Average Crash Rate	Crashes	Crash Rate
LA 3025	358	10.05	147	4.59	-59%	-54.3%
LA 182	178	8.12	85	3.53	-52%	-56.5%
LA 28	206	7.38	99	4.09	-52%	-44.6%
LA 1138	260	16.01	167	10.63	-36%	-33.6%

*calculated as total number of crashes per million VMT

The very impressive results from four roadways were further analyzed to develop a CMF based on a reliable statistical method. The crash data used are from the state crash reporting system at DOTD. After careful evaluation of the data, it was determined to use the total crashes, including crashes identified as intersection crashes in the database in the analysis, because many crashes far away from the three signalized intersections were classified as intersection crashes due to the inconsistencies by police personnel in distinguishing between intersection and access drive-way crashes. The inaccurate coding exists in both the before and after database. The unavailability of all crash reports, particularly from the early years before DOTD scanned all crash reports, made detailed crash report evaluation infeasible.

Since simply comparing crash frequencies before and after a crash countermeasure implementation does not account for the changes in traffic volume and the stochastic nature of crashes, the analysis was conducted based on the principle that the true impact of a crash countermeasure should be the difference between the predicted safety after the crash countermeasure implementation and the predicted safety in the after period if the crash countermeasure were not implemented. Ideally, the predicted expected safety should be calculated by the EB method with a rigorously developed and carefully calibrated safety performance function. Since the models in the HSM Chapter 12 for the two types of roadways are not calibrated with Louisiana data, the following “four-step” procedure introduced by Hauer was used to estimate a CMF for the re-striping projects *[15]*. The details of the safety estimation are summarized as follows:

Step One: Estimating the safety if the re-striping are not installed during the after period, $\hat{\pi}$, and the safety with the re-striping project $\hat{\lambda}$,

$$\hat{\lambda} = N \tag{1}$$

$$\hat{\pi} = \hat{r}_{tf} K \tag{2}$$

where,

$\hat{\lambda}$ = Estimated expected number of crashes in the after time period with re-striping

N = Observed annual crashes after re-striping project

$\hat{\pi}$ = Estimated expected number of crashes in the after period without the re-striping

K = Observed crashes before the re-striping project

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

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

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

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

The results of this application for all four roadways are listed in Table 5.

Table 5
Results from the first step

	$\hat{\lambda}$	$\hat{A}_{avg}$	$\hat{B}_{avg}$	$\hat{r}_{tf}$	$\hat{\pi}$
LA 3025	147	23,888	26,580	0.90	322
LA 182	85	21,947	20,067	1.09	195
LA 28	99	26,115	25,570	1.02	210
LA 1138	167	13,540	13,870	0.98	254

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

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

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

The results of this application for all four roadways are listed in Table 6.

Table 6
Results from the second step

	$\hat{VAR}\{\hat{\lambda}\}$	$\hat{VAR}\{\hat{\pi}\}$	$v\{\hat{A}_{avg}\}$	$v\{\hat{B}_{avg}\}$	$\hat{VAR}\{\hat{r}_{tf}\}$
LA 3025	147	616	0.0398	0.0395	0.0025
LA 182	85	337	0.0430	0.0425	0.0039
LA 28	99	354	0.0396	0.0397	0.0032
LA 1138	167	479	0.0423	0.0424	0.0034

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 for all four roadways are listed in Table 7.

Table 7

Results from the third step

	$\hat{\delta}$	$\hat{\theta}$
LA 3025	175	0.45
LA 182	110	0.43
LA 28	111	0.47
LA 1138	87	0.65

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

$$\hat{\sigma}\{\hat{\delta}\} = \sqrt{\left(\hat{VAR}\{\hat{\lambda}\} + \hat{VAR}\{\hat{\pi}\}\right)} \tag{8}$$

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

The results of this application for all four roadways are listed in Table 8.

Table 8

Results from the fourth step

	$\hat{\sigma}\{\hat{\delta}\} = \sqrt{\text{variance}}$	$\hat{\sigma}\{\hat{\theta}\} = \sqrt{\text{variance}}$
LA 3025	27.62	0.051
LA 182	20.53	0.062
LA 28	21.28	0.062
LA 1138	25.42	0.075

Based on the above calculations, the estimated expected crash reduction for LA 3025 is 175 with a standard deviation of 27.62, 110 for LA 182 with a standard deviation of 20.53, 111 for LA 28 with a standard deviation of 21.28, and 87 for LA 1138 with a standard deviation of 25.42. The estimated expected CMF is 0.45, 0.43, 0.47 and 0.65 for these four roadway segments, respectively. The corresponding standard deviations are 0.051, 0.062, 0.062 and 0.075.

The biggest concern with the re-striping project was whether it increases other types of crashes while reducing the number of rear-end collisions. Based on the distribution of crash types shown in Figure 7, rear-end crashes did decrease 82% on LA 3025, 44% on LA 182, 56% on LA 28, and 47% on LA 1138. On LA 3025, the crash reductions are also evident on all major types of crashes, particularly sideswipe (both directions) and right-angle. A significant decrease in head-on collisions (89%) is observed on LA 1138 while sideswipe (same direction) is decreased by 75%. On LA 28, head-on and sideswipe (same direction) crashes increased while the other types of crashes showed decreasing trend. However, on LA 182, there are slight increases in right-angle, left-turn, and sideswipe (same direction) crashes; however, the 132 crashes with no information on the type of collision from the before time period somewhat affects the comparison.

The crashes by pavement surface conditions and time of the day were also investigated from the before and after periods. As shown in Figure 8, while crash reduction is consistent under both pavement surface conditions, the percentage of reduction is higher under wet pavement conditions than that under dry conditions. Under wet pavement condition, the reduction is 82% for LA 3025, 58% for LA 182, 74% for LA 28, and 33% on LA 1138.

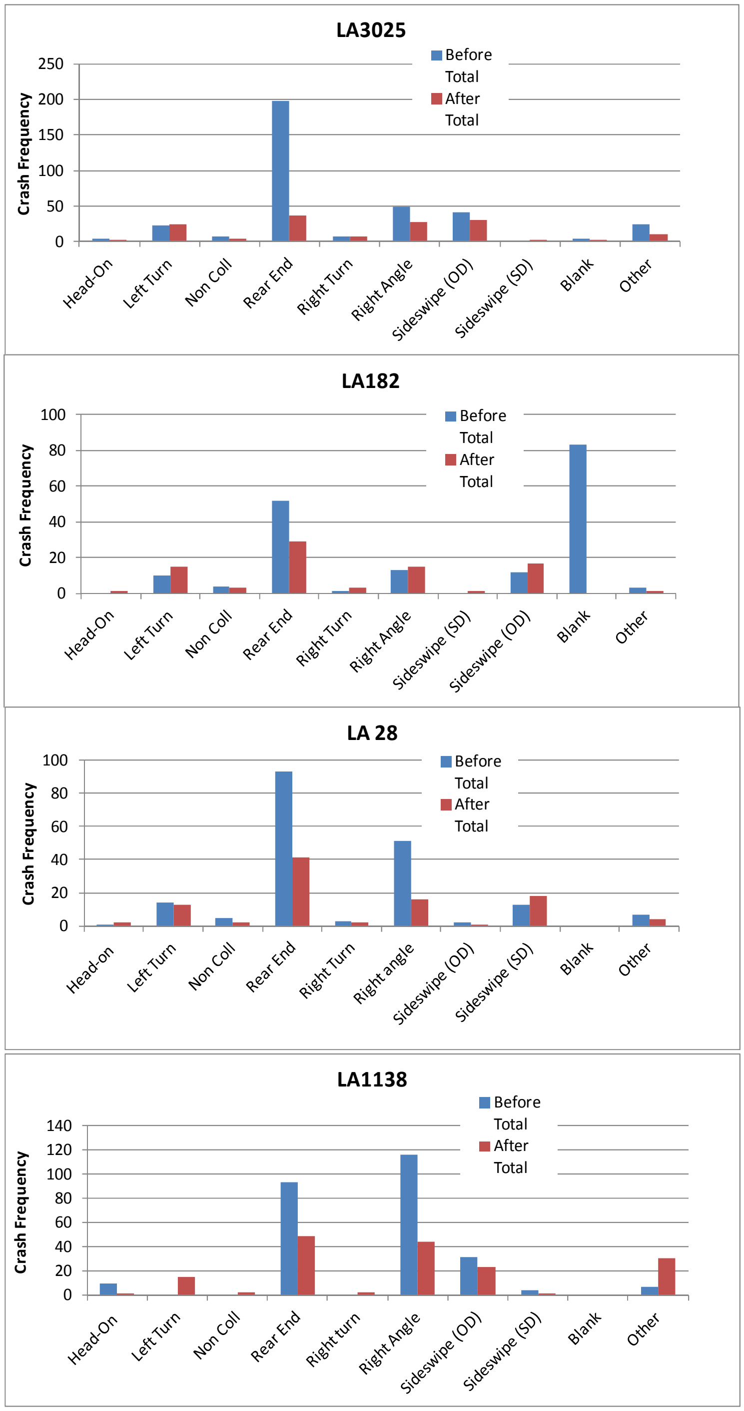

Figure 7
Distribution of crash types

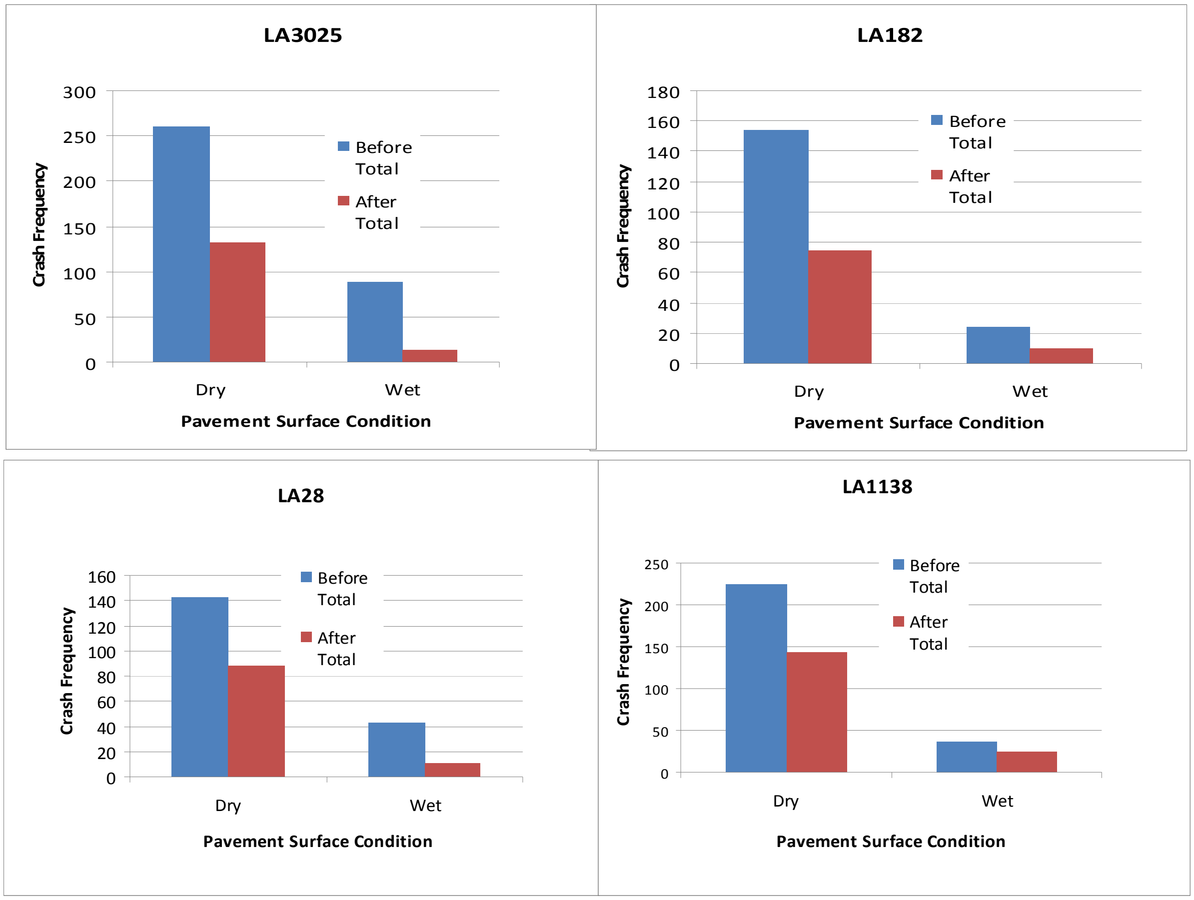

Figure 8
Crash reductions under pavement surface conditions

It is also interesting to note that the crash reduction is almost consistent during different time periods on both roadway segments, as shown in Figure 9.

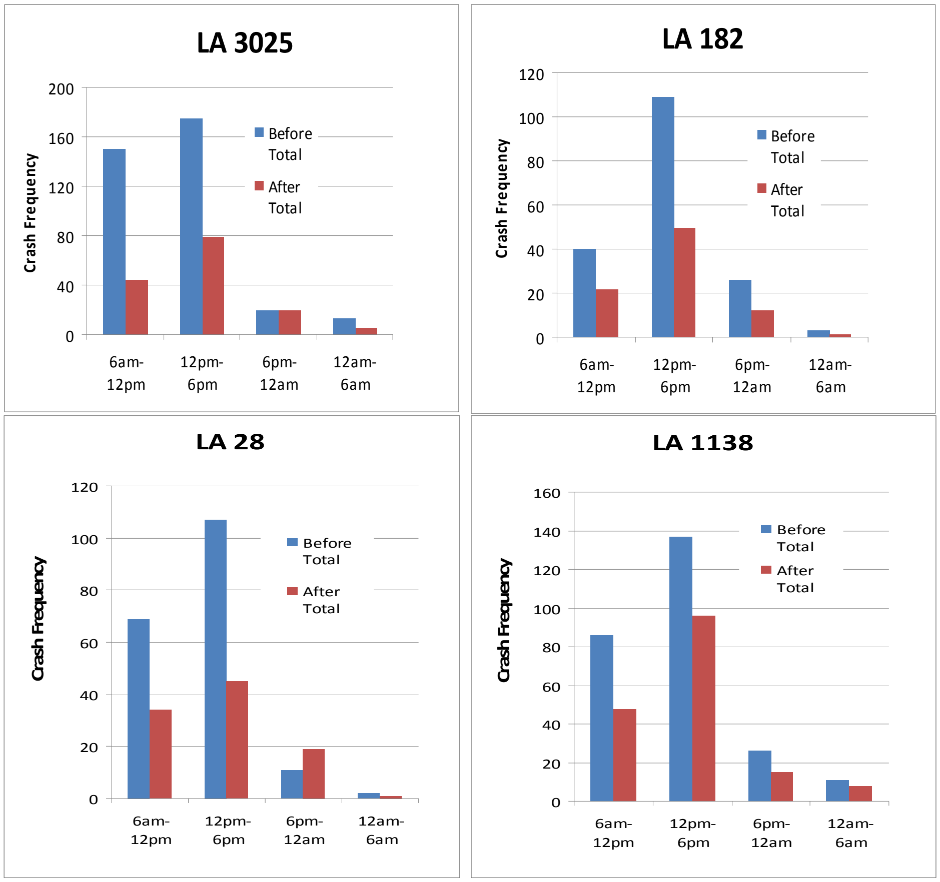

Figure 9
Crash distributions by time of the day

Lastly, the distribution of crash severity before and after the re-striping projects is examined. As shown in Table 9, crash frequencies decrease for both property-damage-only (PDO) crashes and injury crashes except on the LA 3025 segment where fatal crashes increased from zero to two. To investigate the cause of these two fatal crashes, the detailed crash reports were obtained. The reports from the local police show that one fatal crash occurred in 2006 involved a single vehicle running out-of-control and colliding with a utility pole, and the other fatal crash occurred in 2005 at the T-intersection, involving a vehicle on S. College turning left on a permissive green light in front of an opposing through vehicle. Neither fatal crash was related to the change of the roadway. There were no fatal crashes in 2007, 2008, 2009, and 2010, four years after the study time period on this segment.

Table 9
Crash severities before and after the project

Crashes By Severity	LA 3025			LA 182			LA 28			LA 1138		
	Before	After	% Change	Before	After	% Change	Before	After	% Change	Before	After	% Change
Total crashes	358	147	-58.9%	178	85	-52.3%	206	99	-51.9%	260	167	-35.8%
PDO crashes	277	105	-62.1%	124	63	-49.2%	148	76	-48.7%	172	119	-30.8%
Injury Crashes	81	40	-50.6%	54	22	-59.3%	58	23	-60.3%	88	48	-45.4%
Fatal crashes	0	2	increase	0	0	0%	0	0	0%	0	0	0%

The cost of re-striping a roadway per mile including both materials and labor is about $7,105 by the district maintenance crew of the district office or $11,450 by outside contract. Based on the Federal Highway Administration estimation, the average cost for an injury crash is $53,676, and for a PDO is $3,216; this yields a benefit-cost (B/C) ratio of 166 for the LA 182 segment if using an outside contract (assuming the paint lasts about three years) *[18]*. This is the most conservative B/C ratio: it would be larger if in-house maintenance crew costs were used. The benefit-cost ratio for all four segments is shown in Table 10.

Table 10
Estimated benefit-cost ratio for lane converting

Segment	Total Benefits ($)	Total Cost ($)	B/C Ratio
LA 3025	2,753,868	14,100	195
LA 182	1,913,808	11,500	166
LA 28	2,110,212	10,600	199
LA 1138	2,317,488	12,300	188

Crash Modification Factor for Raised Pavement Markers and Striping

Raised Pavement Marker (RPM) and striping are the most common and cost-effective safety features used on highways. RPMs are usually made with plastic, ceramic, or occasionally metal, and come in a variety of shapes, sizes, and colors. Many varieties include a lens or sheeting that enhances their visibility by reflecting automotive headlights. The DOTD started to utilize RPM on experimental basis in 1966. The first large scale installation was on the Mississippi River Bridge at Baton Rouge, Louisiana.

Intuitively convinced by its safety benefits, DOTD has been using RPM for many years on all freeways in the state. As with many highway devices, RPM needs to be replaced periodically to maintain its intended functionality, which requires significant resources. To select the most efficient crash countermeasure under limited resources, the effects of all crash countermeasures need to be understood and quantitatively measured.

Overview of Previous Studies

Many studies were conducted on the evaluation of RPM due to its popularity. But the majority of the studies were focused on RPM installation procedure, durability, retro-reflectivity, costs, and optimum spacing. Relatively few studies have been conducted during the last 30 years on the safety effectiveness of RPM.

Wright et al. evaluated the safety effectiveness of reflective raised pavement markers in 1982 *[19]*. From 1976 to 1978, the Georgia Department of Transportation installed reflective pavement markers on the centerlines of 662 horizontal curves. The study focused on predicting the change in nighttime crashes. Daytime crashes were also used at the same sites for comparison purposes. The results from the study showed 22% reduction of nighttime crashes with comparison to daytime crashes at the same sites.

A before-and-after study was conducted by Kugle et al. in 1984 *[20]*. Two years of before-and-after crash data from 469 Texas sites (varying in length from 0.2 to 24.5 miles) were used for analysis. About 65% study sites were on two-lane roads, the rest are mostly on four-lane roadways. Three different evaluation methods were used in this study. The result showed the nighttime crashes increased by 15% to 30% after RPM installation. Mak et al. performed a study on the same dataset of Kugle et al. to re-examine the impact of RPM on the nighttime crashes *[21]*. In this study, the locations of the previous study were reinvestigated to specify the safety effect of RPM rather than the influence of other countermeasures. A logit model was developed to inspect the statistical significance by means of daytime crashes as the comparison group, which generated mixed results – 4.6%

sites showed significant decrease in nighttime crashes, 10.3% sites showed significant crash increase, and the rest, 85.1%, showed non-significant effects. Griffin analyzed the re-screened data from the Mak et al. study by deploying a different statistical approach *[22]*. Using yoked comparison before and after methodology, the expected change in nighttime crashes following the installation of RPM was estimated to be a 16.8% increase, with the 95% confidence limits between a 6.4% and 28.3% increase. No information regarding the setting (urban or rural) of these roadways was mentioned in the study.

Pendleton used both traditional and EB before-and-after methods to assess the safety impact of RPM on the nighttime crashes on both divided and undivided arterials in Michigan *[23]*. Seventeen locations (length=56 miles) were considered as treatment sites, and 42 sites (length= 146 miles) were used as control sites with no RPM. Crash data for 2 years prior and 2 years after RPM placement were considered for the analysis. Undivided roadways showed an increase in nighttime crashes and divided roadways showed a decrease in nighttime crashes. The EB methodology produced a smaller drop than the conventional before-and-after methodology.

New York State Department of Transportation performed a simple before-and-after safety investigation of RPM in New York *[24]*. In this study, the number of crashes prior and after the RPM placement was compared without controlling for other factors. On unlit suburban and rural roadways there was a non-significant 7% decrease in total crashes and a significant 26% decrease in nighttime crashes. On highway sections with proper lightings, the nighttime crashes were reduced by 8.6% and the total crashes were reduced by 7.4%.

Orth-Rodgers and Associates, Inc. used the same methodology as Griffin to assess the effects of raised pavement markers on nighttime crashes at 91 Interstate highway locations in Pennsylvania *[25]*. The results showed a significant crash increase – 18.1% increase at nighttime crashes, 30% to 47% crash increase at nighttime under wet pavement conditions.

Although the safety benefit of RPM is intuitively felt by drivers in Louisiana, there are not many quantitative studies conducted showing its capability in crash reductions. The National Cooperative Highway Research Program (NCHRP) performed a comprehensive study in 2004 to evaluate the safety effects of raised pavement markers *[26]*. The data from two-lane and four-lane highways were collected from six different states for the analysis. The NCHRP study developed the CMF for rural four-lane freeways that are published in the first edition of HSM as shown in TABLE 11.

Table 11
Potential crash effects of installing snowplowable permanent RPMs from the HSM

Setting (Road Type)	Traffic Volume (AADT)	Crash Type (Severity)	CMF	Std. Error
Rural (Four-lane Freeways)	≤ 20,000	Nightime All Types (All Severities)	1.13	0.2
	20,001-60,000		0.94	0.3
	>60,000		0.67	0.3

The previous studies on the safety effectiveness of RPM had either a limited number of samples or did not separate rural from urban roadways in their analyses, which may explain some of their conflicting results. The NCHRP project did have a large sample size but the results show a negative impact of RPM on roadway safety when AADT is less than or equal to 20,000. There are 40% of rural interstates in Louisiana with AADT less than or equal to 20,000 (97.2% of Louisiana rural freeways are four-lane highways). Most of the rural interstates in Louisiana before 2010 have AADT lower than 60,000. There is a need to substantiate the effect of RPM in order to decide the continuation of RPM on freeways in Louisiana, which is precisely the purpose of the evaluation.

Data Analysis

Two data sets were used for the analysis. The quality of RPM along with pavement striping (center and edge lines) on Louisiana freeways is inspected annually by designated engineers who gives subjective ratings. Three categories of rating (good, fair, and poor) are used to describe the condition of RPM and striping. The segments in poor condition will be scheduled for either RPM replacement or re-striping. The nine years (2002-2010) of RPM and striping ratings for all Louisiana freeways were obtained for the analysis along with the corresponding nine years of crash data. On the average, the good rating for RPM lasts 2.2 years and 3.28 years for striping. During the nine years, a segment would experience several cycles (from good to poor) of ratings for RPM or striping, as shown in Table 12.

Table 12
Sample of RPM annual ratings

		2002	2003	2004	2005	2006	2007	2008	2009	2010
Control Section	Section Length	Striping	Striping	Striping	Striping	Striping	Striping	Striping	Striping	Striping
450-91	2.54	G	G	P	G	G	F	F	F	P
450-91	1.36	F	F	G	G	G	F	F	F	P
450-91	3.4	F	F	G	G	G	F	F	F	P
450-91	1.17	F	F	G	G	G	F	F	F	P
450-91	0.13	F	F	G	G	G	F	F	F	P
450-91	0.38	F	F	G	G	G	F	F	F	P

The RPM and striping ratings are made independently based on the control section, a segmentation method used by DOTD. In total, there are close to 900 miles of freeways in 533 segments. Within each defined segment, the roadway major attributes, such as lane width, shoulder width, number of lanes, type of pavement, AADT, and etc., remain the same. The nine years of crashes were populated to each segment based on their longitudinal and latitudinal coding.

Because of the difference in segment length and AADT, crash frequency cannot be directly used for comparison. Thus, crash rate (crashes per 100 million VMT) is calculated for each segment. Due to the difference in interstate design and operation, the analysis is conducted for rural and urban separately.

There are nine possible annual rating combinations, such as GG, GF, GP, FG, FF, FP, PG, PF, and PP, with the first letter for RPM and the second for striping (G as good, F as fair and P as poor). The summary of ratings is listed in Table 13.

Table 13
Summaries of freeway segments in different ratings

Freeway Location	Number of Segments in Each Rating Group								
	GG	GF	GP	FG	FF	FP	PG	PF	PP
Rural	606	85	171	63	110	140	75	31	285
Urban	1,028	189	280	156	214	266	141	88	734
Total	1,634	274	451	219	324	406	216	119	1,019

Note: Segments under major maintenance/reconstruction marked as ***C*** *are not counted*

Excluding the mixed ratings from RPM and striping, the first focus of the analysis was only on the cases with both ratings in the same category. Figure 10 compares of the crash rate for the rural freeway segment, where the overall average crash rate for both RPM and striping with quality rating k, $\overline{R}_k$ is computed as:

$$\overline{R}_k = \frac{\sum_i \overline{r}_{ki}}{N} \qquad \overline{r}_{ki} = \frac{\sum_j r_{kij}}{M_k} \tag{10}$$

where,

$\bar{r}_{ki}$ = average crash rate over nine years on segment j with both rating as k

r_{kij} = crash rate of segment j at year i with both ratings as k

N = number of segments

M_k = number of years both ratings in k for segment j

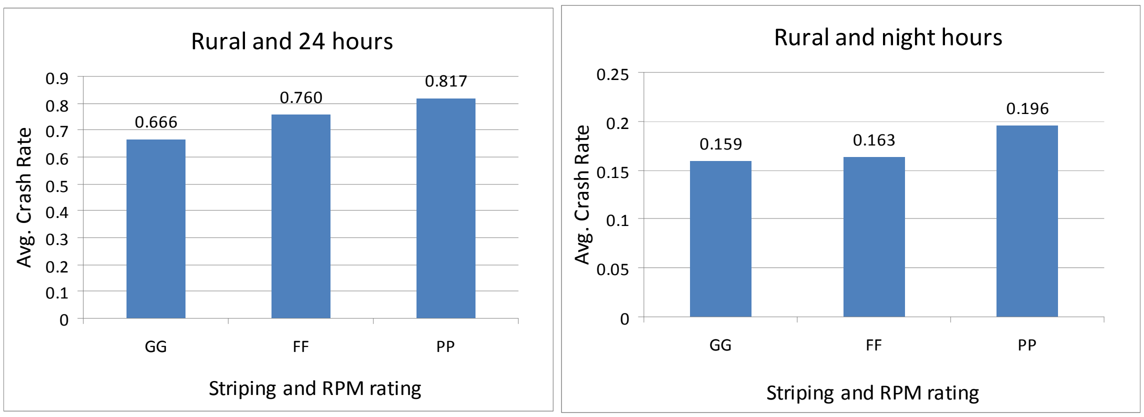

Figure 10
Average crash rate by different ratings on rural freeway

It is encouraging to see that the quality of RPM and striping does make a difference in the crash rate. As the combined ratings go from good to poor, the overall average crash rate increases. Since the RPM is particularly important at night for outlining traveled lanes, the nighttime crash rate is computed with the same level of AADT, which shows the similar trend. The increasing crash rate from good rating to poor rating is 23% for 24-hours crash rate calculation, and 23% for nighttime crash rate estimation. However, as shown in Figure 11, the overall average crash rates do not reveal any positive effect of RPM and striping on the urban freeways, which is similar to the CMF listed in the first edition of HSM.

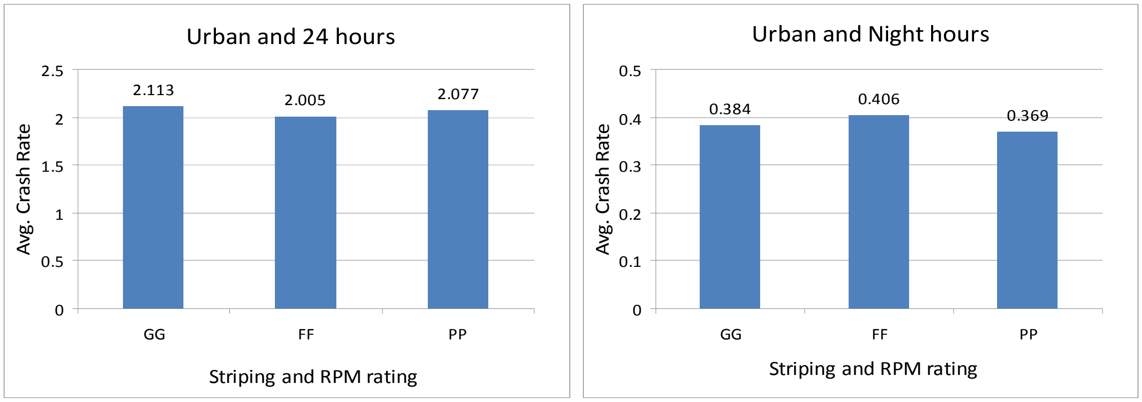

Figure 11
Average crash rates by different ratings on urban freeway

It is a challenge to estimate the safety effect of RPM and striping separately since both have somewhat similar functionalities. Figure 12 illustrates how overall average crash rates on rural freeways vary by either RPM or striping ratings at both 24 and night hours.

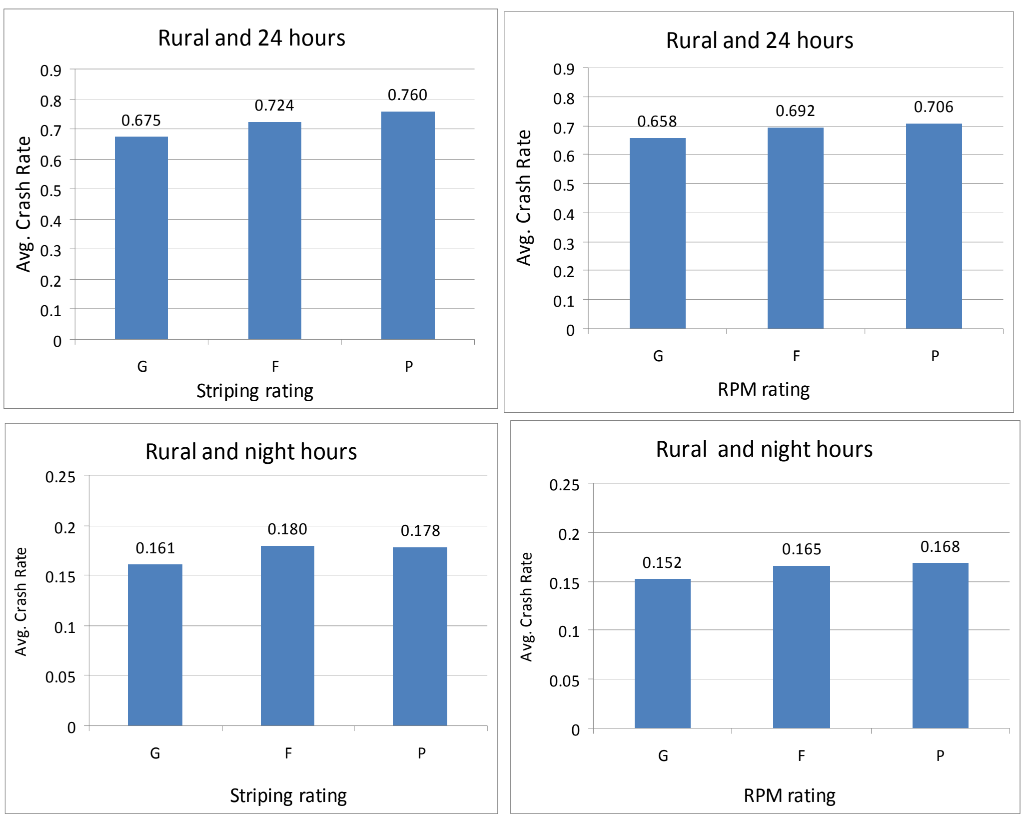

Figure 12
Average crash rate by single rating (RPM or striping)

The positive safety effect is still evident even with only one single rating, as shown in Figure 12, where the lowest crash rate is always associated with a good rating on either RPM or striping. It is recognized that with one feature (RPM or striping) at rating k, the rating for the other feature can be in all three categories. That is, while a RPM is in good rating, the rating for striping can be good, fair and poor at the same time and location, which explains why the difference in the average crash rate between rating good and poor for a single feature is not as big as the difference in the combined ratings between GG and PP. Nevertheless, the initial data analysis does demonstrate the safety effect of RPM and striping independently.

The initial analysis results show the difference in crash rate between good and poor ratings for RPM and striping. Whether or not these differences are significant in the statistical terms was then examined, in which the rating from each year on all rural freeway segments are used in the statistical test as one independent data sample instead of the segment averages. The difference of crash rate under good and poor ratings is examined by the t-test at three AADT levels. The results of the statistical testing are listed in Table 14.

Table 14
Results of statistical tests

Roadway Type	Feature	Crash Rate at	t-test for Equality of Means						
			t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
								Lower	Upper
AADT ≤ 20,000									
Rural	RPM	Night	-1.781	489	0.076	-0.033	0.018	-0.069	0.003
Rural	RPM	24 Hrs	-1.101	489	0.271	-0.065	0.059	-0.181	0.051
Rural	RPM+Striping	Night	-2.603	309	0.010	-0.063	0.024	-0.110	-0.015
Rural	RPM+Striping	24 Hrs	-2.591	309	0.010	-0.212	0.082	-0.373	-0.051
20,000≤AADT ≤ 60,000									
Rural	RPM	Night	-2.665	816	0.008	-0.038	0.014	-0.066	-0.010
Rural	RPM	24 Hrs	-3.249	816	0.001	-0.142	0.044	-0.228	-0.056
Rural	RPM+Striping	Night	-2.285	492	0.023	-0.047	0.020	-0.087	-0.007
Rural	RPM+Striping	24 Hrs	-2.840	492	0.005	-0.168	0.059	-0.284	-0.052
AADT ≤ 60,000									
Rural	RPM	Night	-2.128	1339	0.033	-0.025	0.012	-0.049	-0.002
Rural	RPM	24 Hrs	-2.573	1339	0.010	-0.102	0.040	-0.180	-0.024
Rural	RPM+Striping	Night	-2.800	889	0.005	-0.045	0.016	-0.077	-0.013
Rural	RPM+Striping	24 Hrs	-3.504	889	0.000	-0.186	0.053	-0.289	-0.082

The statistic testing results shows that the safety effect of RPM varies slightly by AADT. The crash rate difference between two ratings is, indeed, statistically significant for RPM alone and RPM plus striping for AADT higher than 20,000 as shown in Table 14. The negative lower and upper bound of the estimated mean difference at 95% confident level ascertains the positive effect of RPM and striping, jointly and separately for the rural freeways with AADT higher than 20,000. Although the similar results are also seen on the upper part of the table showing the results for all rural freeways, the testing results on the middle part of the table are slightly different. For the rural freeway segments with AADT less than 20,000, the crash rate difference between two RPM ratings is only statistically significant at nighttime (at 90% confidence level). The positive upper bound of 0.003 indicates the existence of uncertainty.

The results from this study are somewhat different from the CMF given by the HSM. Since crash rate (used in our study) and CMF are two different concepts, we cannot simply compare their values. However, the RPM effect expressed by the CMF and crash rate difference can be illustrated by the probability calculation based on the information listed in Table 1 and from this study. For AADT under 20,000, probability of getting positive safety effect is calculated as 0.26 with 1.13 CMF and a standard error of 0.2. For the same AADT, the probability of positive safety effect is calculated as 0.97 with the crash rate difference of -0.033 and a standard error of 0.018. Both calculations are displayed in Figure 13.

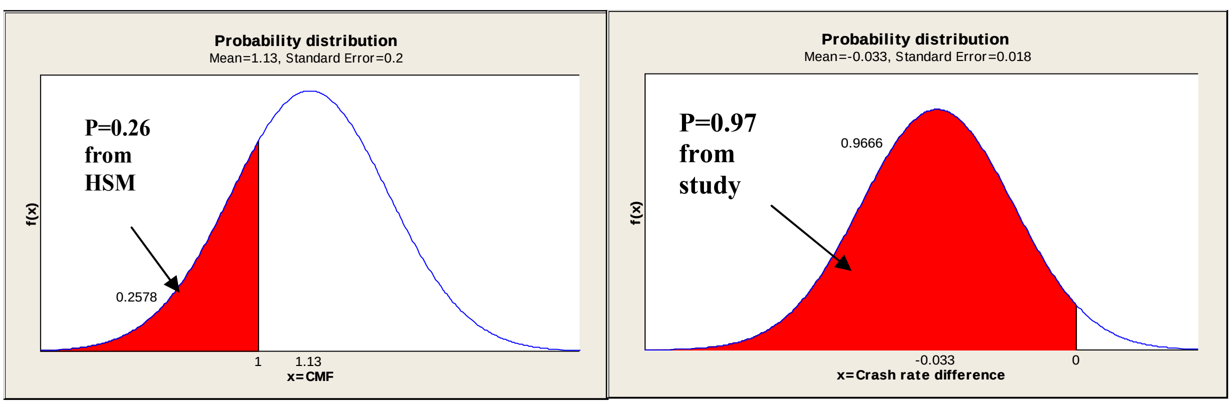

Figure 13
Probability comparison

For AADT between 20,000 and 60,000, the probability of getting positive RPM effect is 1.0 from this study and is 0.58 from the HSM. As expected, the test on the urban freeways shows no significant difference (either positive or negative) in crash rate under all scenarios.

Although the analysis with crash rate was considered the most reliable method for the evaluation, another method was also used to explore the safety effects of RMP and striping at nighttime. Lacking a Safety Predictive Model for freeway, the direct application of many safety evaluation methods recommended by the HSM is not suitable for this unique case. A so-called "with and without" crash analysis was performed, which not only considers AADT changes but also accommodates the difference in segment length. The analysis method divides the ratings of each segment in nine years into two groups as "with" (with good rating) and "without" (with poor rating). Two adjustment factors, $\boldsymbol{r_a(j)}$ and $\boldsymbol{r_s(j)}$, are developed to account for AADT changes during the analysis years and different sample size between "with" and "without" groups.

$$r_a(j) = \frac{\overline{A}_{wj}}{\overline{A}_{WTj}} \tag{11}$$

$$r_s(j) = \frac{N_{wj}}{N_{WTj}} \tag{12}$$

where,

$\overline{A}_{wj}$ = average AADT of "with" group for segment j

$\overline{A}_{WTj}$= average AADT of "without" group for segment j

N_{wj}= number of years under "with" group for segment j

N_{WTj} = number of years under "without" group for segment j

The analysis results are given in Table 15, which show a clear crash reduction at night for RPM.

Table 15
"With" and "Without" crash analysis for rural freeways at nighttime

Feature Type	Number of Sections	Expected Crashes With (Good)	Expected Crashes Without (Poor)	Expected Crash Reduction	% Reduction
RPM	114	641	675	34	5.30%
Striping	77	476	477	1	0.20%

Table 16
CMF values for RPM and RPM and striping both for rural freeways

Highway Type	Feature	Crash Hour	Rating	N	Mean	CMF
AADT≤ 20,000						
Rural	RPM	Night	Good	291	0.139	0.81
			Poor	200	0.172	
Rural	RPM	24 Hrs	Good	291	0.635	0.91
			Poor	200	0.700	
Rural	RPM+Striping	Night	Good	225	0.138	0.69
			Poor	86	0.201	
Rural	RPM+Striping	24 Hrs	Good	225	0.644	0.75
			Poor	86	0.856	
20,000 ≤ AADT≤ 60,000						
Rural	RPM	Night	Good	436	0.141	0.79
			Poor	382	0.179	
Rural	RPM	24 Hrs	Good	436	0.596	0.81
			Poor	382	0.738	
Rural	RPM+Striping	Night	Good	329	0.148	0.76
			Poor	165	0.195	
Rural	RPM+Striping	24 Hrs	Good	329	0.602	0.78
			Poor	165	0.770	
AADT≤ 60,000						
Rural	RPM	Night	Good	745	0.153	0.86
			Poor	596	0.178	
Rural	RPM	24 Hrs	Good	745	0.655	0.87
			Poor	596	0.757	
Rural	RPM+Striping	Night	Good	606	0.155	0.78
			Poor	285	0.200	
Rural	RPM+Striping	24 Hrs	Good	606	0.655	0.78
			Poor	285	0.841	

DISCUSSION OF RESULTS

Four-lane to Five-lane Urban Roadway Conversions for Safety

The crash reduction from the re-striping projects is impressive. Crash countermeasures, as listed in the first edition of the HSM, seldom yield CMF values smaller than 0.5. The estimated CMF and standard deviation on both roadway segments indicate a 100% confidence that a re-striping project reduces crashes since the estimated CMF plus the three standard deviation is still much less than one (0.60 for LA 3025 and 0.62 for LA 182, 0.66 for LA 28, and 0.88 for LA 1138).

Examining crashes three years after the lane conversion, we have found different pictures. Figure 14 shows the crash reduction on LA 3025 sustainable, which further confirms the effectiveness of the crash countermeasure even the segment experiences a 10 % increase in the average AADT from the 2004-2006 to 2008-2010.

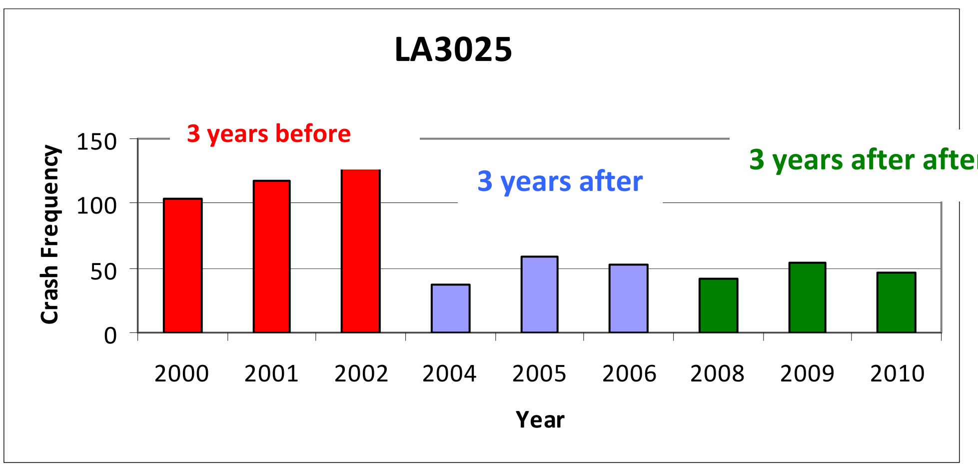

Figure 14
Crashes by year on LA 3025

However, the crash frequency on LA 28 does not show the same trend. The annual crashes started to increase in the fourth year (2009) and peaked in the fifth year (2010), as shown in Figure 15 that also includes the crash rate by year. Considering other crash contributing factors that may change over the years generating unknown impact on the crashes, it is hard for the research team to offer any discussion even after talking to the district engineer. One possible explanation may come from the crash data recording practice.

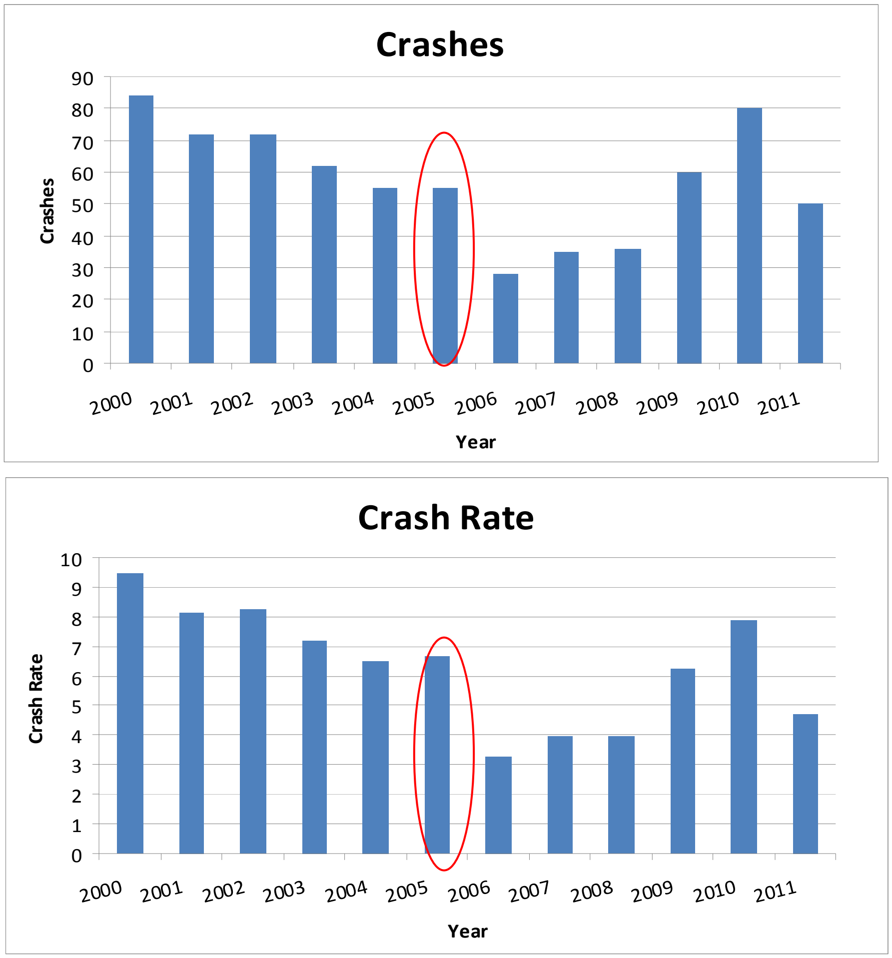

Figure 15
Annual crashes and crash rate on LA 28

Figure 16 shows annual crashes on LA 1138. In 2005, the sixth year after the re-striping project, there is a spike in crashes. Hurricane Rita in 2005 had a huge impact on the Lake Charles area that may explain the crash spike in 2005. The sudden crash increase in 2010 is also suspected to have something to do with crash data collection practice.

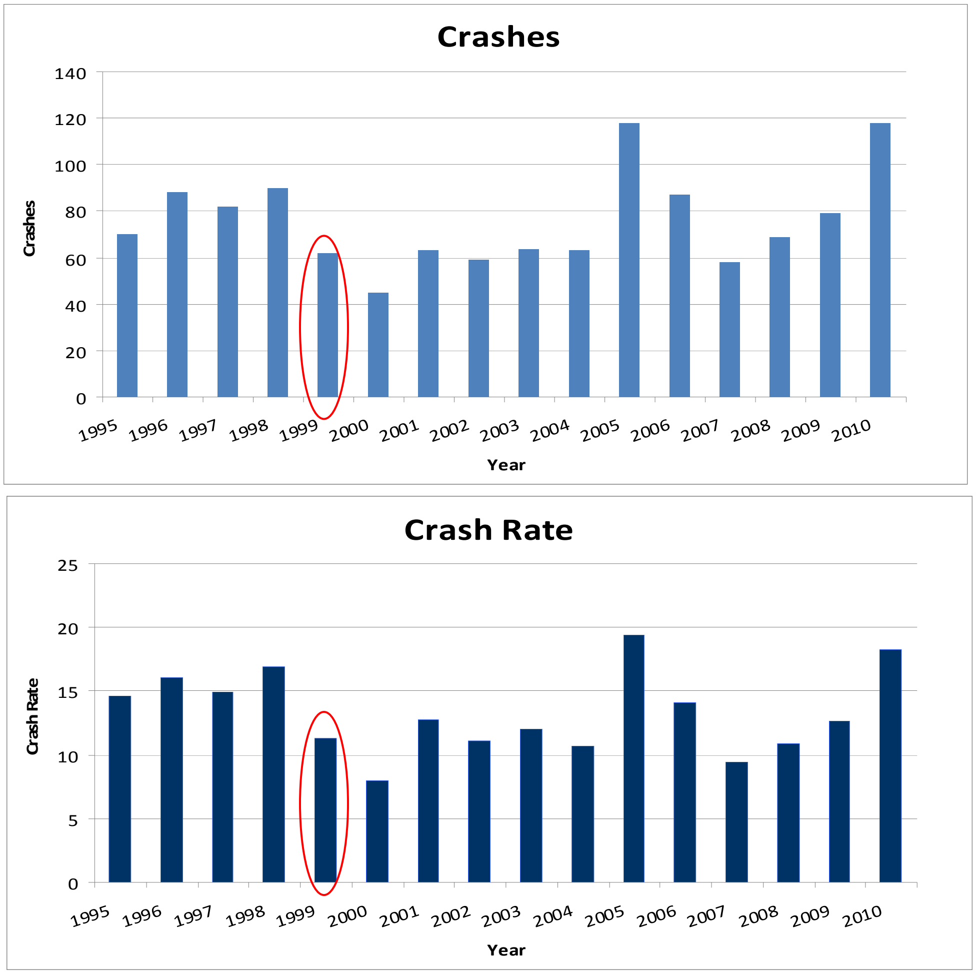

Figure 16
Annual crashes and crash rate on LA 1138

Although intersection crashes are not excluded from the analysis due to recognized problems in crash coding, the effectiveness is likely not overestimated since all intersections' configurations remain the same before and after the re-striping projects. It is believed that the effect of the intersection coding problem is minimized, if not totally canceled, because it exists consistently before and after the project. While nothing was changed except the lane configuration on LA 3025, there was a speed limit reduction (from 50 mph to 45 mph) on 44% of LA 182 segment after the re-striping project. Without collecting speed data before and after the re-striping project and speeding enforcement camera on this segment, the impact of speed limit change on operating speed is not clear. However, the numerous past studies on speed have shown that operating speed is seldom controlled by speed limit unless enforcement is present; and speed change has no statistically significant effect on crash frequency but does associate with crash severity. Thus, it is possible that the higher injury reduction on LA 182 shown in Table 9 is somewhat associated with the speed limit change.

The success on these four roadway segments demonstrates the need for flexibility in selecting the best safety improvement project under the existing constraints (financial or otherwise). For each specific traffic crash problem, there are always a set of crash countermeasures ranking from the highest to the lowest in crash reduction capability and B/C ratio. When the most desirable options are restricted in immediate application, it is better to do something that can reduce crashes rather than passively wait for future, possibly unrealistic, opportunities. Changing the problematic four-lane undivided roadway segments to a roadway type that is not used in new construction proves to be a very effective crash countermeasure. If and when funds do become available in the future, it is easy to convert these two five-lane roadway segments to a boulevard roadway type, a concept very much promoted today in urban and suburban areas in Louisiana.

Examining the successful crash reduction cases, it is also important to note that one-size-fits-all solutions do not always prevail in highway safety. Although our study shows impressive results, caution must be taken when applying this crash countermeasure in other locations. Particular attention must be made to not only the driveway or access point density but also the type and size of traffic generators along the roadway. With sufficient segments (samples), it would be interesting to determine if the presence and size of retail business make a difference in the magnitude of the CMF.

Under exactly the same conditions such as traffic volume, pavement width, and roadside development, which roadway (four-lane undivided vs. five-lane) is safer? The analysis results presented in this study confidently identifies the winner, which is in line with the facts listed in the Minnesota Statewide Urban Design and Specifications and a National Cooperative Highway Research Program (NCHRP) report published in 25 years ago *[27, 28]*. The Minnesota document lists the crash rate is 6.75 for four-lane undivided roadway and 4.01 for five-lane with center turn lane. In the NCHRP report, it states, "Conversion from a four-lane undivided cross section to a five-lane TWLTL cross section with narrower lanes reduced accident rates, on the average, by 45%." This study shows a higher than 50% crash reductions. However, the application experiments with the two models from the Chapter 12 of HSM yield the opposite conclusion. That is, under exactly same conditions, the calculated expected crashes are higher on five-lane roadway than that on four-lane undivided roadway, which may show a need for improvement on the next edition of HSM.

Performance of Raised Pavement Marker and Striping

Among the three analyses, all showing the positive impact of RPM on rural freeway safety in Louisiana, we believe that the results from the statistical test offer the most reliable information. The other two analyses are based on the segment average over the nine years for either AADT or crashes, which not only greatly reduces the number of samples but also the accuracy of the results.

It is possible that other crash countermeasures were implemented on the rural freeways during those nine analysis years. Since the RPM condition cycle is short (average 2.2 years in good rating) and annual RPM ratings are different at different locations, the effect of other crash countermeasures would not significantly affect the results. Based on the analysis, work-zone presents the biggest impact on freeway safety. The highest crash rates are consistently associated with the freeway segments under construction. When a freeway segment was under construction or major maintenance, the RPM and striping rating was coded as C, thus excluded from the analysis.

Although the rating on RPM and striping are subjective, it is believed that the errors caused by the subjective evaluation could be consistent over space and in time. The effect of subjective rating on the analysis results should be minimal, if not totally ignorable, when the analysis is focused on the difference between good and poor conditions. Concerning potential errors in the subjective rating, the RPM under fair conditions was not included in the analysis.

In summary, this study indicates clearly that RPM does make a difference on rural freeway safety under all AADT conditions in Louisiana. The RPM should be continually maintained on rural freeways in the state. The study also confirms that there are no safety benefits for RPM on urban freeways probably due to better lighting conditions. For well-lit urban freeways, there is no need to implement RPM except on ramps at freeway entrances and exits.

CONCLUSIONS

The analysis conducted in this project enable us to draw the following conclusions:

1. Converting four-lane undivided urban roadways to one five-lane roadways with middle lanes for left turns is an effective and feasible solution to reduce crashes on urban undivided roadways with lots of driveways in Louisiana.
2. RPM helps reduce crashes on rural freeways in Louisiana.

RECOMMENDATIONS

Two recommendations are made based on this project to enhance roadway safety in Louisiana.

- Perform a safety evaluation study on all undivided four-lane urban roadways to see if there is a crash problem associated with the current lane layout. A further evaluation on the existing ROW should be conducted to see the feasibility of lane-converting project. The re-striping project should be warranted if the first evaluation demonstrates the need and the second confirms the feasibility.
- Continue the current practice in RPM inspection and replacement of rural freeways in the state.

ACRONYMS, ABBREVIATIONS, AND SYMBOLS

AADT	Annual 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
MCF	Method Correction Factor
NCHRP	National Cooperative Highway Research Program
PDO	Property Damage Only
RPM	Raised Pavement Marker
RTM	Regression-To-Mean
SHSP	Strategic Highway Safety Plan
VMT	Vehicle Mile Traveled

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APPENDIX

Calculation Details for CMF Evaluation for Four-Lane to Five-Lane Conversion

Table 17
Crash and AADT data for LA 3025

Control Section	Logmile From	Logmile To	Section Length	Before					After				
				2000	2001	2002	Total K(j)	ADT	2004	2005	2006	Total L(j)	ADT
828-23	0.328	1.556	1.228	104	118	136	358	26,580	37	58	52	147	23,888

$$\hat{\lambda} = L = 147,\ V\hat{A}R(\hat{\lambda}) = L = 147$$

$$r_d = \frac{After\,Years}{Before\,Years} = \frac{3}{3} = 1,\ r_{tf} = \frac{\hat{A}_{avg}}{\hat{B}_{avg}} = \frac{23888}{26580} = 0.90,\ \hat{\pi} = \hat{r}_{tf} K = 322$$

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

$$v^2(\hat{A}_{avg}) = (1 + \frac{7.7}{3} + \frac{1650}{23888^{0.82}})^2 \times 10^{-4} = 0.0016,\ v^2(\hat{B}_{avg}) = (1 + \frac{7.7}{3} + \frac{1650}{26580^{0.82}})^2 \times 10^{-4} = 0.0016$$

$$V\hat{A}R(\hat{r}_{tf}) = (\hat{r}_{tf})^2[v^2(\hat{A}_{avg}) + v^2(\hat{B}_{avg})] = 0.00255,\ V\hat{A}R(\hat{\pi}) = (r_d)^2[(\hat{r}_{tf})^2 K + K^2 V\hat{A}R(\hat{r}_{tf})] = 616$$

$$\hat{\delta} = \hat{\pi} - \hat{\lambda} = 175,\ V\hat{A}R(\hat{\delta}) = V\hat{A}R(\hat{\pi}) + V\hat{A}R(\hat{\lambda}) = 763,\ \hat{\sigma}(\hat{\delta}) = 27.622$$

$$\hat{\theta} = (\hat{\lambda}/\hat{\pi})/[1 + V\hat{A}R\{\hat{\pi}\}/\hat{\pi}^2] = 0.45$$

$$V\hat{A}R(\hat{\theta}) = \frac{\theta^2[(V\hat{A}R(\hat{\lambda})/\lambda^2) + (V\hat{A}R(\hat{\pi})/\pi^2)]}{[1 + (V\hat{A}R(\hat{\pi})/\pi^2)]^2}] = 0.0026,\ \hat{\sigma}(\hat{\theta}) = 0.051$$

Table 18
Crash and AADT data for LA 182

Control Section	Logmile From	Logmile To	Section Length (mi)	Before					After				
				2000	2001	2002	Total K(j)	ADT	2004	2005	2006	Total L(j)	ADT
032-02	12.129	13.129	1.00	57	71	50	178	20,067	22	32	31	85	21,947

Detailed calculation:

$$\hat{\lambda} = L = 85, V\hat{A}R(\hat{\lambda}) = L = 85$$

$$r_d = \frac{After\,Years}{Before\,Years} = \frac{3}{3} = 1, r_{tf} = \frac{\hat{A}_{avg}}{\hat{B}_{avg}} = \frac{21947}{20067} = 1.09,\ \hat{\pi} = \hat{r}_{tf} K = 195$$

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

$$v^2(\hat{A}_{avg}) = (1 + \frac{7.7}{3} + \frac{1650}{21947^{0.82}})^2 \times 10^{-4} = 0.0016,\ v^2(\hat{B}_{avg}) = (1 + \frac{7.7}{3} + \frac{1650}{20067^{0.82}})^2 \times 10^{-4} = 0.0016$$

$$V\hat{A}R(\hat{r}_{tf}) = (\hat{r}_{tf})^2[v^2(\hat{A}_{avg}) + v^2(\hat{B}_{avg})] = 0.0039, V\hat{A}R(\hat{\pi}) = (r_d)^2[(\hat{r}_{tf})^2 K + K^2 V\hat{A}R(\hat{r}_{tf})] = 337$$

$$\hat{\delta} = \hat{\pi} - \hat{\lambda} = 110, V\hat{A}R(\hat{\delta}) = V\hat{A}R(\hat{\pi}) + V\hat{A}R(\hat{\lambda}) = 422,\ \hat{\sigma}(\hat{\delta}) = 20.53$$

$$\hat{\theta} = (\hat{\lambda}/\hat{\pi})/[1 + V\hat{A}R\{\hat{\pi}\}/\hat{\pi}^2] = 0.43$$

$$V\hat{A}R(\hat{\theta}) = \frac{\theta^2[(V\hat{A}R(\hat{\lambda})/\lambda^2) + (V\hat{A}R(\hat{\pi})/\pi^2)]}{[1 + (V\hat{A}R(\hat{\pi})/\pi^2)]^2}] = 0.0038,\ \hat{\sigma}(\hat{\theta}) = 0.062$$

Table 19
Crash and AADT data for LA 28

Control Section	Logmile From	Logmile To	Section Length (mi)	Before					After				
				2000	2001	2002	Total K(j)	ADT	2004	2005	2006	Total L(j)	ADT
074-01	0.14	1.06	0.92	72	72	62	206	25,570	28	35	36	99	26,115

Detailed calculation:

$$\hat{\lambda} = L = 99,\ V\hat{A}R(\hat{\lambda}) = L = 99$$

$$r_d = \frac{After\ Years}{Before\ Years} = \frac{1}{1} = 1,\ r_{tf} = \frac{\hat{A}_{avg}}{\hat{B}_{avg}} = \frac{26115}{25570} = 1.02,\ \hat{\pi} = \hat{r}_{tf} K = 210$$

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

$$v^2(\hat{A}_{avg}) = (1 + \frac{7.7}{3} + \frac{1650}{26115^{0.82}})^2 \times 10^{-4} = 0.0016,\ \ v^2(\hat{B}_{avg}) = (1 + \frac{7.7}{3} + \frac{1650}{25570^{0.82}})^2 \times 10^{-4} = 0.0016$$

$$V\hat{A}R(\hat{r}_{tf}) = (\hat{r}_{tf})^2[v^2(\hat{A}_{avg}) + v^2(\hat{B}_{avg})] = 0.003,\ V\hat{A}R(\hat{\pi}) = (r_d)^2[(\hat{r}_{tf})^2 K + K^2 V\hat{A}R(\hat{r}_{tf})] = 354$$

$$\hat{\delta} = \hat{\pi} - \hat{\lambda} = 111,\ V\hat{A}R(\hat{\delta}) = V\hat{A}R(\hat{\pi}) + V\hat{A}R(\hat{\lambda}) = 453,\ \ \hat{\sigma}(\hat{\delta}) = 21.284$$

$$\hat{\theta} = (\hat{\lambda}/\hat{\pi})/[1 + V\hat{A}R\{\hat{\pi}\}/\hat{\pi}^2] = 0.47$$

$$V\hat{A}R(\hat{\theta}) = \frac{\theta^2[(V\hat{A}R(\hat{\lambda})/\lambda^2) + (V\hat{A}R(\hat{\pi})/\pi^2)]}{[1 + (V\hat{A}R(\hat{\pi})/\pi^2)]^2}] = 0.0039,\ \hat{\sigma}(\hat{\theta}) = 0.062$$

Table 20
Crash and AADT data for LA 1138

Control Section	Logmile From	Logmile To	Section Length (mi)	Before					After				
				2000	2001	2002	Total K(j)	ADT	2004	2005	2006	Total L(j)	ADT
810-06	2.78	3.85	1.07	88	82	90	260	13,870	45	63	59	167	13,540

Detailed calculation:

$$\hat{\lambda} = L = 167, V\hat{A}R(\hat{\lambda}) = L = 167$$

$$r_d = \frac{After\,Years}{Before\,Years} = \frac{1}{1} = 1, r_{tf} = \frac{\hat{A}_{avg}}{\hat{B}_{avg}} = \frac{13540}{13870} = 0.98,\ \hat{\pi} = \hat{r}_{tf} K = 254$$

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

$$v^2(\hat{A}_{avg}) = (1 + \frac{7.7}{3} + \frac{1650}{13540^{0.82}})^2 \times 10^{-4} = 0.0018,\ v^2(\hat{B}_{avg}) = (1 + \frac{7.7}{3} + \frac{1650}{13870^{0.82}})^2 \times 10^{-4} = 0.0018$$

$$V\hat{A}R(\hat{r}_{tf}) = (\hat{r}_{tf})^2[v^2(\hat{A}_{avg}) + v^2(\hat{B}_{avg})] = 0.0034, V\hat{A}R(\hat{\pi}) = (r_d)^2[(\hat{r}_{tf})^2 K + K^2 V\hat{A}R(\hat{r}_{tf})] = 479$$

$$\hat{\delta} = \hat{\pi} - \hat{\lambda} = 87, V\hat{A}R(\hat{\delta}) = V\hat{A}R(\hat{\pi}) + V\hat{A}R(\hat{\lambda}) = 646,\ \hat{\sigma}(\hat{\delta}) = 25.415$$

$$\hat{\theta} = (\hat{\lambda}/\hat{\pi})/[1 + V\hat{A}R\{\hat{\pi}\}/\hat{\pi}^2] = 0.65$$

$$V\hat{A}R(\hat{\theta}) = \frac{\theta^2[(V\hat{A}R(\hat{\lambda})/\lambda^2) + (V\hat{A}R(\hat{\pi})/\pi^2)]}{[1 + (V\hat{A}R(\hat{\pi})/\pi^2)]^2}] = 0.0056,\ \hat{\sigma}(\hat{\theta}) = 0.075$$