Effectiveness of Inexpensive Crash Countermeasures to Improve Traffic Safety

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Effectiveness of Inexpensive Crash Countermeasures to Improve Traffic Safety

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DEDICATION

Three million martyrs in the liberation war of Bangladesh in 1971.

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CHAPTER 1: INTRODUCTION

1.1. Motivation

Roadway safety is a major concern because of the enormous economic and societal losses caused by costs occurring from traffic crashes. Economic and societal costs include productivity, property damage, injury, travel delay, legal, emergency management, and insurance. The estimated total economic cost of the U.S. roadway traffic crashes in 2013 was $242 billion. In 2013, there were 30,057 fatalities in 5,687,000 police-reported traffic crashes, which means that on average 83 fatalities occurred every day, or 1 fatality in every 17 minutes. Additionally, 1,591,000 people were injured and 4,066,000 crashes caused property damage only (PDO). The fatality rate in 2013 was 1.09 (defined by fatalities per 100 million vehicle miles traveled [VMT]). The injury rate per 100 million VMT in 2013 was 77 and the fatality rate per 100,000 populations was 10.35 (Blincoe et al., 2015). Although significant improvements have been observed in the recent years (e.g., fatal crashes decreased by 14% from 2008 to 2013, percentage of alcohol-impaired driving fatalities has declined from 48% in 1982 to 31% in 2013), we need effective and insightful research to improve overall highway safety.

Louisiana continuously faces a traffic safety problem even in the recent years. The traffic fatality rate (fatalities per 100 million VMT) has been consistently higher than the national average despite significant improvements made in the past several years. According to the Louisiana Department of Transportation and Development (DOTD) report, there were 706 fatalities, 70,645 injuries, and 109,786 PDO crashes in 2013 (Schneider, 2013). Fatal crashes and injury crashes have decreased by 0.5% and 2.3%, respectively, from 2012 to 2013. The estimated total economic cost of the Louisiana traffic crashes in 2013 was $5.6 billion. Figure 1.1 shows the traffic fatality rate per 100 million VMT for the Southeastern Association of State Highway and Transportation Officials (SASHTO) states (Alabama, Arkansas, Florida, Georgia, Kentucky, Louisiana, Mississippi, North Carolina, South Carolina, Tennessee, Texas, Virginia, West Virginia). It clearly indicates that Louisiana is not doing well compared to the national average. Thus, improving the safety of road users remains a top priority of transportation and safety planners in Louisiana. In recent years increased attention has been directed at determining the effective and inexpensive crash countermeasures for prompt and steady safety improvement.

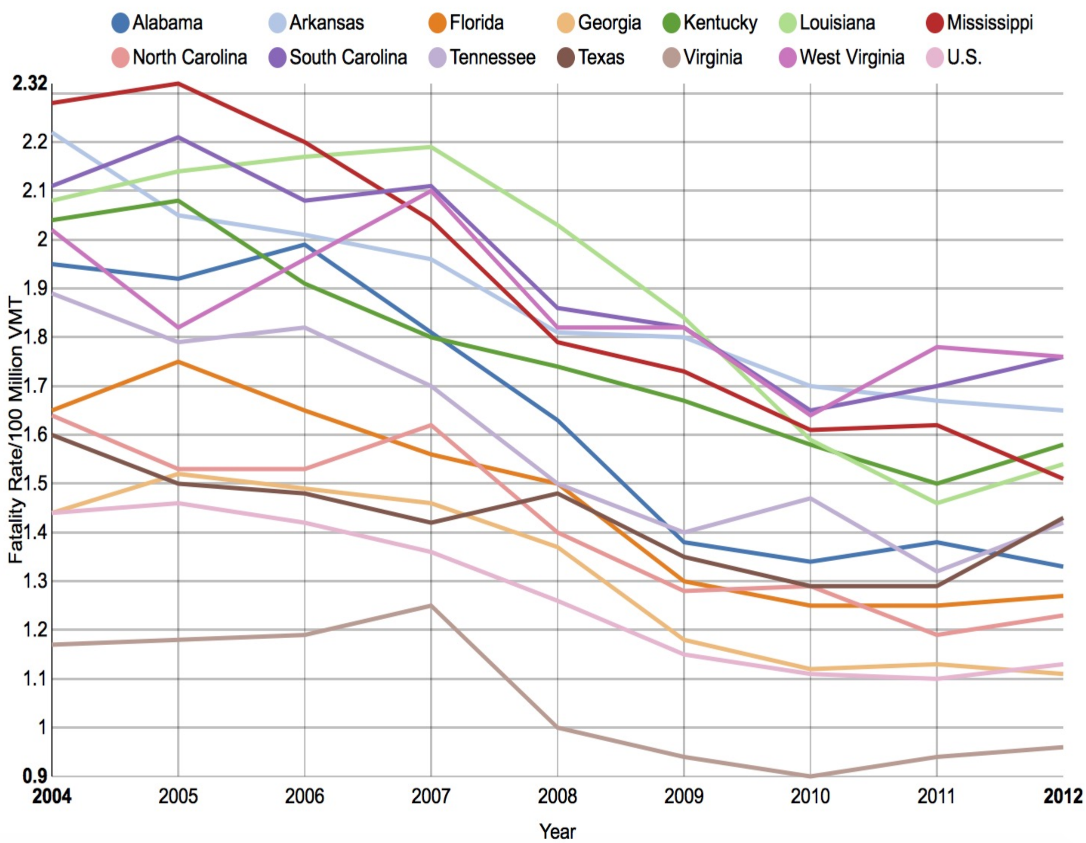

Figure 1.1. Traffic fatality fate per 100 million VMT

The investigation on the occurrence of crashes can be used for risk assessment during system development phase, and post-crash analysis to study why and how crashes occurred and what can be done to prevent crashes. The scientific study of crash or accident analysis started nearly 100 years ago. The development of accident theories over the years is illustrated in Figure 1.2.

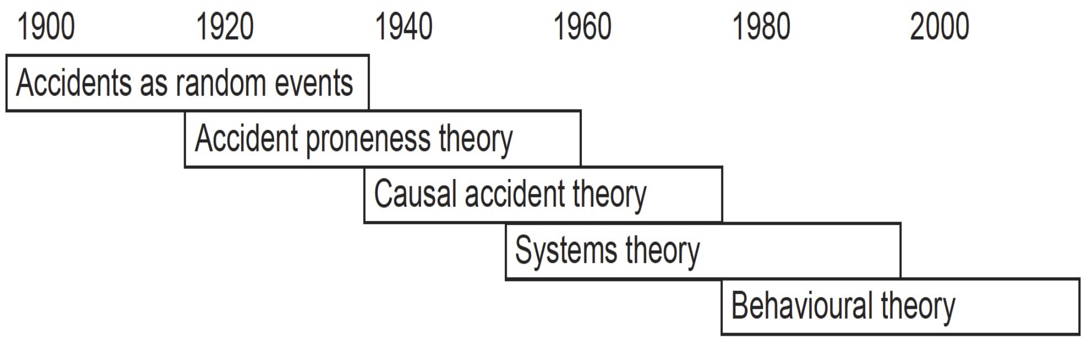

Figure 1.2. Timeline of accident theory (Elvik, 2009)

The first three theories [from 1900 to 1980] cannot provide full satisfactory solutions to tackle road safety problems. Newer accident models, based on systems thinking approach, classified as systems model, suggest describing the characteristic performance of the system as a whole, rather than specific and discrete so-called association-effect mechanisms. A major difference between systemic accident/crash models is that systemic accident/crash models describe an accident/crash process as a complex and interconnected network of events rather than an association-effect chain of incidents. The behavioral theory is gaining pace based on the theories proposed after 1980.

The goal of roadway safety research is to reduce crash frequencies and degree of crash severities through various actions. One of the most important tasks in highway safety analysis is the identification of countermeasures that can make significant safety improvements. Traffic safety is usually derived from the recorded number of crashes or the number of fatalities or injuries. Total number of crashes or injured road users recorded during a certain period is the result of complex transportation systems. Moreover, the safety researchers encounter two major issues during analysis: under-reporting of traffic crashes and random variation in the recorded crashes.

Targeting crashes at roadway segments has been the focus of safety related projects at all levels. With limited resources, DOTD is particularly interested in the actions that will yield compelling practical and inexpensive results. Thus a comprehensive study on the selection of Louisiana specific effective inexpensive countermeasures is needed. This dissertation is an exploration of determining a toolset to contribute in this perspective. The dissertation research targets following issues while identifying the appropriate inexpensive crash countermeasures:

- Identify crash countermeasures that have great potential to reduce number of crashes (by type) and crash severities.
- Select alternatives, perform benefit-cost analysis, and prioritize the appropriate countermeasures.
- Evaluate safety effectiveness of the countermeasures.

1.2. Research Approach

A roadway traffic crash is considered a rare, random, multifactor event always preceded by a state in which one or more roadway users fail to cope with the prevailing travel environment. A crash can be dissected by time and associated elements. One of the most important tasks in highway safety analysis is to identify crash contributing factors so that the most effective countermeasures can be implemented to improve safety. For example, by knowing specific risk factors, safety engineers can develop appropriate countermeasures. Moreover, road users play a major role in the creation of safe roadways, but their roles are shaped in part by the design, policy, environment, technological revolution, and social norms of the road transportation system.

Economic evaluation of traffic safety measures is considered as a very important tool for policy makers. In this study, the Six Sigma tool DMADV (Define-Measure-Analyze-Design-Verity) procedure is used to understand, identify, and disseminate best practice to ensure that cost-effectiveness in crash countermeasures has been initiated. Proper ranking based on several criteria (like crash reduction, severity reduction, installation easiness, and benefit-cost ratio) will help in designing the most promising inexpensive countermeasures.

Crash countermeasures with high safety effects and low implementation costs are always preferable. This study targets to reduce traffic crashes and severities by introducing a DMADV tool for selecting appropriate inexpensive countermeasures to improve safety on an aggregate or disaggregate level.

1.3. Research Questions

The safety effectiveness of inexpensive countermeasures for Louisiana addresses three major research questions:

- How does an effective systems tool help in defining and improving the problem statement?
- Are the selected inexpensive countermeasures effective on the basis of safety and economy?

- Are the findings practice-ready?

1.4. Research Hypothesis

The research hypothesis of the dissertation is: the selected inexpensive countermeasures are of high performance and cost-effective.

1.5. DMADV Tool

The Six Sigma is considered as a data-driven organized approach to eliminate defects from any kind of system, from manufacturing to transactional and from production to service design. Two major processes are used in the Six Sigma:

- The Six Sigma DMAIC (Define, Measure, Analyze, Improve, and Control) is an improvement system for existing processes for incremental improvement.
- The Six Sigma DMADV (Define, Measure, Analyze, Design, and Verify) is an improvement system used to develop new processes or products.

This research addresses the issues in identifying the most effective crash countermeasures suitable for Louisiana. The research uses the Six Sigma tool DMADV to perform the research. The basic framework of the Six Sigma method is shown in Figure 1.3.

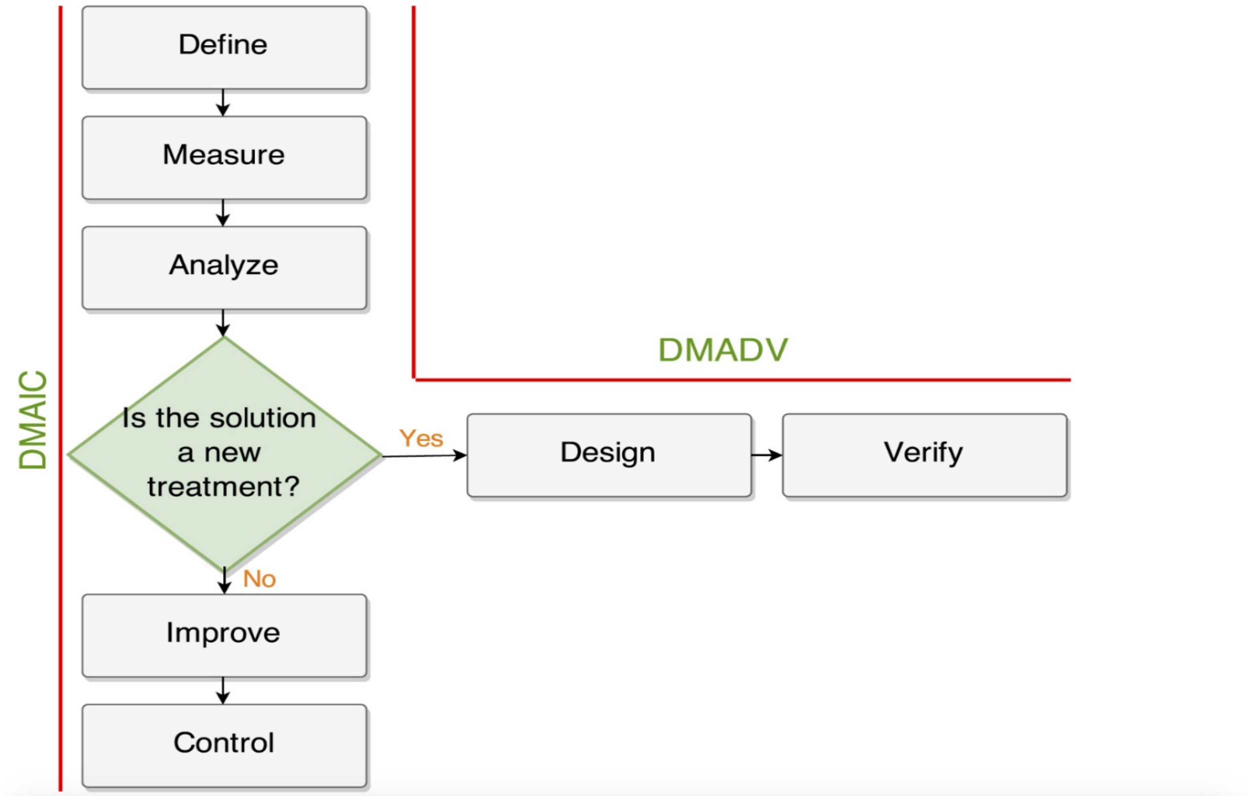

Figure 1.3. The Six Sigma procedure

DMAIC gives emphasis on the procedural improvement; on the other hand, DMADV provides more emphasis on newer product development. The process flow chart for determining the most effective inexpensive countermeasures is shown in Figure 1.4. It clearly shows the difference between our research methodology and the DMAIC procedure.

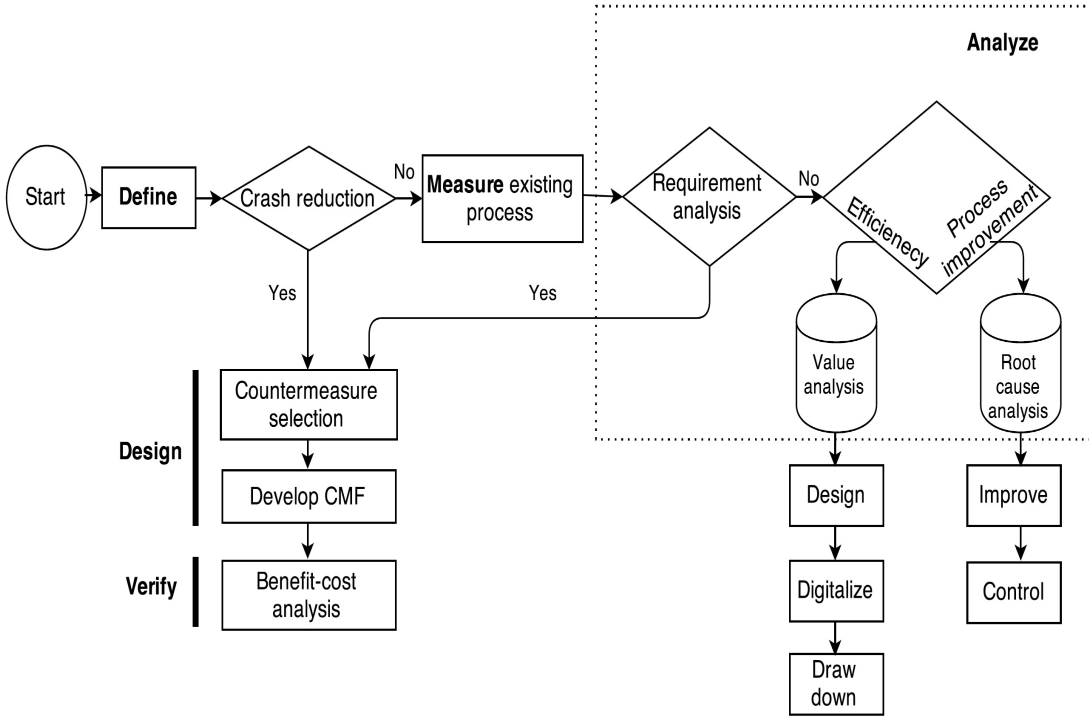

Figure 1.4. Process flow chart

1.5.1. Define

The defining phase is the first phase of the DMADV approach. In this phase, we need to define the problem statement. This phase defines the goals and boundaries of the Six Sigma project in terms of the requirements and the procedures to direct the research improving upon current process or designing newer product. The research problem is associated with the selection of the most appropriate inexpensive countermeasures for Louisiana. The following activities were performed in this regard:

- **Identify road user needs:** The objective of this study is to reduce the number of crashes on highway. The reduction of number of crashes will benefit both the highway authority (voice of business) as well as the roadway users (VOC). The Metropolitan Planning Organizations (MPO) perform some key functions like establishing a setting, alternative evaluation, maintain a long term transportation plan, development of transportation improvement plan, and issues related to the Moving Ahead for Progress in the 21st Century Act (MAP-21). The MPOs of Louisiana usually organize public attendance meetings on various issues. An extensive analysis on these records was performed to identify the voice of road users.

- **Identify and plan to improve the process:** The systems approach is defined by using process mapping which is shown in Table 1.1. A SIPOC (suppliers, inputs, process, outputs, and customers) is one of the efficient tool that summarizes the inputs and outputs in a simple tabular form. This advanced process map helps define the project periphery, can recognize the data collection methodology, and identifies the tools required to carry out the measure and analysis activity.

Table 1.1. SIPOC method

Suppliers	Inputs	Process	Outputs	Customers
Department of Transportation, insurance company, police department, Highway Safety Manual	Crash data, driver data, crash countermeasures	Crash analysis, before-after study, exploratory data analysis	Crash reduction	Roadway users

1.5.2. Measure

The measuring phase includes the research synthesis of the available inexpensive countermeasures in Louisiana. A rating system will be developed in the analysis phase after gaining information from research synthesis. Rating of the countermeasures would be based on several criteria: 1) crash reduction, 2) fatality reduction, 3) installation task, 4) advantages, 5) disadvantages, 6) maintenance cost, and 7) benefit-cost analysis. The documents published by the Federal Highway Administration (FHWA) were used for information collection.

- **Research synthesis:** In the preliminary analysis, a list of twenty inexpensive countermeasures was developed after conducting research synthesis on the avaiable resouces in Louisiana. Considering the adverse effects and lower safety effects, some of the countermeasures were removed from the list. Eleven countermeasures were finally selected for the analyze phase. The list of countermeasures consists of the following:
  - Roadside cable barrier
  - Rumble strips
  - Edge line
  - Lane conversion (four lane undivided to three lane undivided)
  - Lane conversion (four lane undivided to five lane undivided)
  - Safety edge
  - Rear-facing flashing beacons
  - On-pavement horizontal markings
  - Raised pavement markers (RPM)
  - Wider longitudinal pavement markings
  - Post-mounted delineators
- **Check sheet:** The listed countermeasures were passed through an effectiveness

check sheet based on installation cost, available safety effectiveness, and benefit-cost analysis in order to determine a more precise list.

1.5.3. Analyze

The analysis phase uses the available tools to investigate the performance of the design products. Eleven countermeasures were finally selected for the prioritization matrix development. The numerical ratings were assigned to each countermeasure based on five performance measures: 1) crash reduction, 2) fatality reduction, 3) installation task, 4) maintenance cost, and 5) benefit-cost ratio. Table 1.2 lists the ratings criteria. The average rating was calculated with the information obtained from the research synthesis analysis for each countermeasure. The prioritization matrix shown in Table 1.3 was developed for each criteria rating and the overall rating (based on the combination effect of five selection criteria) of the available countermeasures in Louisiana. The countermeasures with overall rating **A** were considered for further analysis. These countermeasure are four lane to five lane conversion, edge line, and raised pavement markers.

Table 1.2. Ranges of the ratings

No.	Criteria	Rating A	Rating B	Rating C
1	Roadway traffic crash reduction	>10%	6-10%	1-5%
2	Roadway traffic fatality reduction	>20%	11-20%	1-10%
3	Intensity of installation task	Easy	Medium	Difficult
4	Construction and maintenance cost	Low	Medium	High
5	Benefit-cost ratio	1:11 or higher	1:6 to 1:10	1:1.5 to 1:5

Table 1.3. Prioritization matrix

Countermeasure	Crash reduction	Fatality reduction	Installation task	Maintenance cost	Benefit-cost analysis	Overall rating
Roadside cable barrier	A	B	A	B	A	B
Rumble strips	A	B	A	B	A	B
Edge line	A	B	A	A	A	A
Lane conversion (four to three)	A	A	B	B	B	B
Lane conversion (four to five)	A	A	A	A	A	A
Safety edge	A	A	B	A	B	B
Rear-facing flashing beacons	A	B	B	B	B	B
On-pavement horizontal mark	A	A	B	B	B	B
Raised pavement markers	B	A	A	A	A	A
Wider longitudinal pavement markings	A	A	B	A	B	B
Post mounted delineators	A	A	A	B	B	B

1.5.4. Design

In the design phase, the design procedures of the Crash Modification Factor (CMF) development of the three selected countermeasures were described. These procedures are described in Chapters 2, 3, and 4.

1.5.5. Verify

In the verifying phase, the design was justified by examining the value of CMF. The countermeasure is effective if the CMF is less than one. The research also conducted benefit-cost analyses to investigate cost-effectiveness of the selected countermeasures. These procedures are described in Chapters 2, 3, and 4.

1.6. Dissertation Organization

The organization of the dissertation is as follows. In Chapter 1, the background and motivation, objectives, methodology and outline of the research are included. The first three phases of the DMADV procedure are also described in the Chapter 1. This dissertation uses the three-paper dissertation model. The titles of the published papers are: Four-lane to Five-lane Urban Roadway Conversions for Safety (published in the Journal of Transportation Safety and Security. Vol. 5, No. 2, pp. 106-117, 2013), Investigating Safety Impact of Edge Lines on Narrow, Rural Two-lane Highways by Empirical Bayes Method (published in the Transportation Research Record. Vol. 2433, pp. 121-128, 2014), and Investigating the Safety Impact of Raised Pavement Markers on Freeways in Louisiana (published in the International Journal of Engineering Research and Innovation. Vol. 5, No. 2, pp. 74-80, 2013). These three papers are described in Chapters 2, 3, and 4. Chapter 5 is the commercialization chapter. The commercialization of the research product is described in this chapter. Moreover, concluding remarks, findings, and practical uses are listed in this Chapter. Figure 1.5 shows the organization of the dissertation.

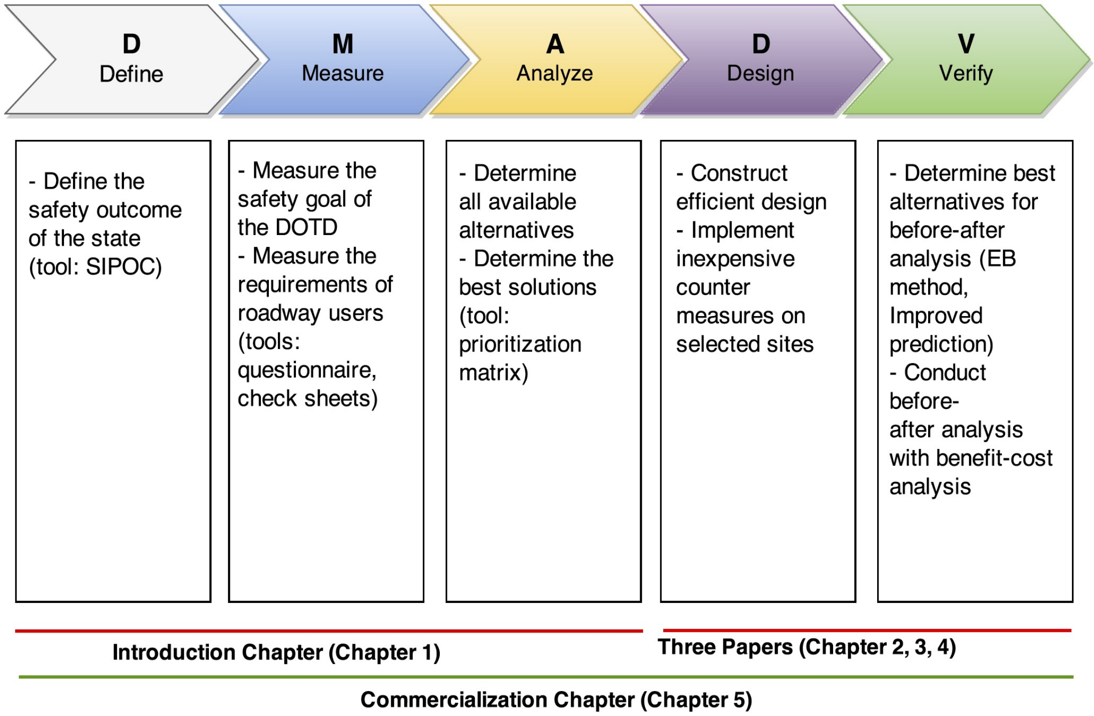

Figure 1.5. Organization of the dissertation

1.7. Dissertation Contributions

Figure 1.6 describes the dissertation contributions. This dissertation combines the DMADV approach with countermeasure selection and effectiveness measurement. The research appeals not only to transportation engineers, but also constitutes advancements in systems tool development and commercialization.

- **Systems engineering contributions:** This research provided a framework for DMADV tools to use it in transportation safety improvements.

- **Traffic engineering contributions:** The contributions offered by these innovations are of two types: (1) aggregate and disaggregate level inexpensive countermeasures selection and (2) the development and implementation of a flexible and extensible approach to building CMFs. These methods provided a comprehensive modeling framework to reduce crashes. Reduction of crashes from the research findings can be considered as a significant contribution in transportation safety engineering.

- **Commercialization contributions:** This research developed an efficient commercialization tool which can be used in any aggregate or disaggregate level countermeasure selection and successful implementation. The commercialization tool would work as a single tool to fit in different circumstances for getting efficient and effective inexpensive crash countermeasures.

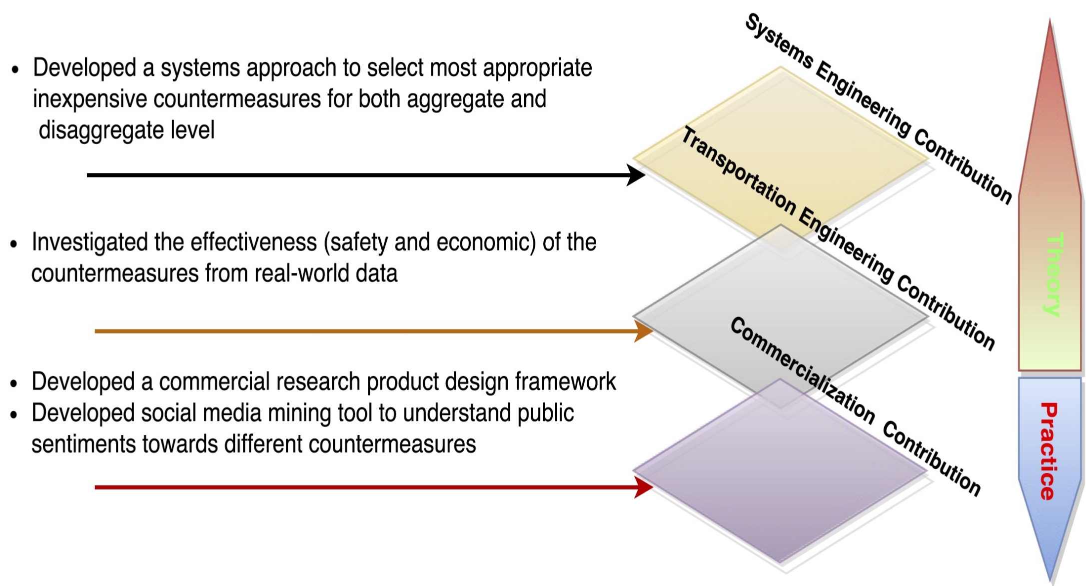

Figure 1.6. Dissertation contributions

CHAPTER 2: FOUR-LANE TO FIVE-LANE URBAN ROADWAY CONVERSION TO IMPROVE SAFETY

Abstract

Undivided roadways have consistently exhibited low safety performance, particularly in urban or suburban areas where roadside development is relatively intense. Changing a four-lane undivided roadway to a divided roadway by either building a boulevard cross-section or installing a physical barrier is a desirable option to improve safety performance of an undivided roadway, but it requires significant resources. This paper introduces a crash countermeasure successfully implemented on four different segments of four-lane undivided roadways in Louisiana. This crash countermeasure is to change an undivided four-lane roadway to a five-lane roadway with a center lane as a two-way-left-turn-lanes (TWLTL) by re-striping pavement markings without increasing pavement width. Although the five-lane roadway is no longer an acceptable roadway type in Louisiana, the impressive crash reductions on all four roadway segments demonstrate it as a feasible solution under constrained budgetary conditions. Based on the statistical analysis with six years of crash data (three years before and three years after excluding the implementation year), the crash modification factors for the roadways are estimated to be less than 0.65 with a standard deviation less than 0.07. Unsurprisingly, the biggest crash reduction comes from the rear-end collisions, but other types of collision are also reduced with this method.

2.1. Introduction

The Louisiana Strategic Highway Safety Plan (SHSP) is to reach 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 in recent years such as the Highway Safety Manual (HSM) (AAS, 2010), Countermeasures that Work from the National Highway Transportation Safety Administration (NHTSA) (NAT, 2009) and the Crash Modification Factor Clearinghouse. The effectiveness of many crash countermeasures have been quantified by scientific methodologies.

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 (fatalities per 100 million VMT), undivided highways have the overall highest total crash rate (crashes per million VMT) and crash injury rate (crash injuries per million VMT) in the U.S. A high proportion of the crashes are rear-end collisions on this type of roadway. The undivided multilane roadway presents a common type of roadway in both urban and rural areas. In Louisiana, there are 1,530 miles of undivided multilane roadways and most of them are four-lane highways on the state Department of Transportation and Development System. Ninety-three percent of these roadways are in urban and suburban areas. Installing physical separations either by barrier or by green space (boulevard) has been the most recommended crash countermeasure for the problem. With sufficient pavement 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 less desirable based on past experiences with five-lane roadway operations in many urban and suburban areas. Louisiana has established policies discouraging the design of five-lane roadways for new roads, and seldom considers it as an option in reducing crashes on undivided multilane roadways. This research collected data from four sites with this inexpensive countermeasure installation. This research aims to develop Louisiana specific CMF for this countermeasure by using before-after crash analysis.

2.2. Literature Review

Little research has been conducted to evaluate the safety effectiveness from four-lane to five-lane options. The Minnesota Statewide Urban Design and Specifications lists the crash rate of 6.75 for four-lane undivided roadways and 4.01 for five-lane undivided roadways with a center turn lane. A National Cooperative Highway Research Program (NCHRP) report published 25 years ago states that conversion from a four-lane undivided cross section to a five-lane TWLTL cross section with narrower lanes reduced crash rates, on average, by 45% (Harwood, 1986).

Although little documentation was found on four-lane to five-lane conversions, there have been several projects throughout the country converting four-lane roadways to 3-lane roadways (one lane in each direction with a center turn lane) for many years in the past for the benefits of safety particularly the safety of pedestrians and cyclists on urban and suburban areas. As mentioned in several documentations, this conversion is suitable for roadways with Annual Average Daily Traffic (AADT) less than 20,000 or for roadways with a peak hour traffic volume less than 1,750 (IOW, 2012). The case studies summarized by Knapp show a consistent improvement in highway safety from 21 roadways in seven states with AADT from 8,400 to 24,000 (Knapp et al., 2003). Another important factor in consideration is access density or access spacing. As pointed out by a Minnesota study, three-lane roadway is suitable for high access density under AADT less than 20,000 (Byers and Drager, 2011).

Under exactly the same conditions such as traffic volume, driveway type and density, lighting and parking, which roadway (four-lane undivided vs. five-lane roadway) is safer? Although roadway users generally prefer a five-lane layout to a four-lane undivided roadway for convenience, the answer to the question should come from crash data analysis. However, there is no CMF listed in the first edition of the HSM for converting a four-lane undivided urban roadway to a five-lane roadway, and, to our knowledge, no before-after studies have been conducted in the last decade on the impact of such conversions.

2.3. Methodology

The five lane roadways with a TWLTL are considered a common multilane design alternative for urban and suburban arterials. It has two through lanes in both directions and a center lane dedicated for left-turn maneuvers for the driveways and minor intersections. Adding a TWLTL has the tremendous benefit of adding a continuous left turn option which helps in reducing delays as well as crashes. Its also very attractive for the business owners on the roadways with a high driveway density.

The basic approach of the research is to convert the urban four-lane undivided roadways (4U) to five-lane undivided roadways with a TWLTL (5T). The before-after conversion is shown in Figure 2.1. The methodology is comprised of three tasks: 1) selection of the segments, 2) conduct before-after analysis, and 3) conduct crash characteristics analysis.

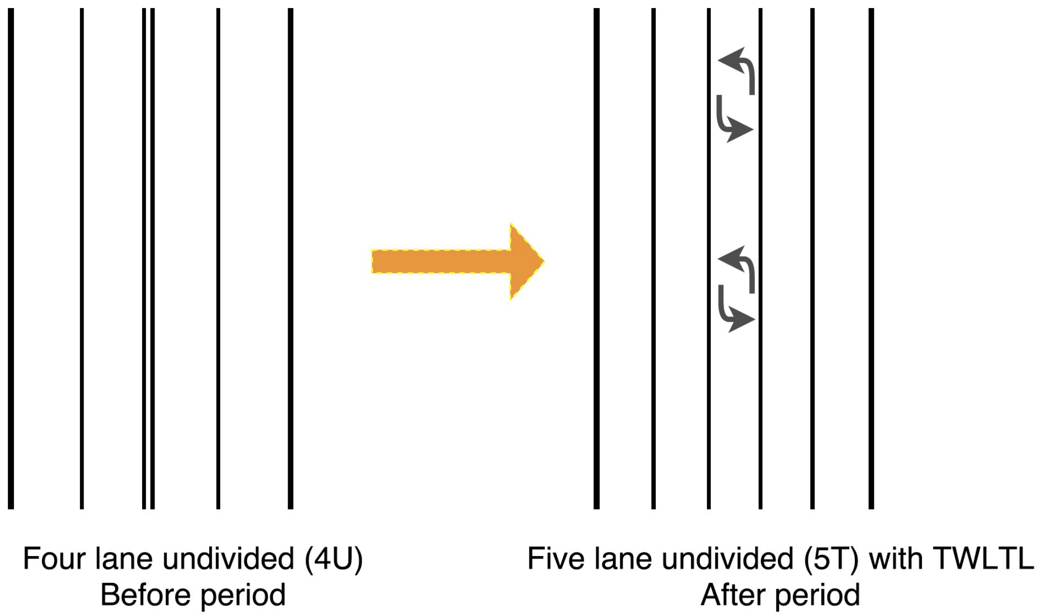

Figure 2.1. Before-after roadway condition

I have selected four different segments for the study. The description of the final four segments is stated in Table 2.1. In Figure 2.2, the before installation roadway condition is shown. The after installation is shown in Figure 2.3.

Table 2.1. Information on the roadway segments

Dist.	Highway	Control Section	Logmile from	Logmile to	Section length (mi)	Install year	No. of Drive ways	Location
3	LA 3025	828-23	0.328	1.556	1.228	2003	13	Lafayette
3	LA 182	032-02	12.129	13.129	1.000	2007	14	Opelousas
8	LA 28	074-01	0.140	1.060	0.920	2005	20	Alexandria
7	LA 1138	810-06	2.780	3.850	1.070	1999	50	Lake Charles

Figure 2.2. Before condition of LA 182

Figure 2.3. After condition of LA 182

2.3.1. Segment Selection

The other control sections with four lane to five lane conversion are: LA 93 in Sunset from LA 182 to 400 ft. west of the I-49 W.S.R. (installation year= 2009), LA 14 in New Iberia from 400 ft. east of Queen City Dr. to Vena St. (installation year= 2007), LA

14 (Charity) in Abbeville from 600 ft. west of LA 14-Bypass to Viola St. (installation year= 2011), LA 14-Bypass in Abbeville from 400 ft. west of Lyman to 600 west of Gauraud St. (installation year= 2011), US 190 in Eunice from Moosa Blvd to 300 ft. west of 12th St. (installation year= 2012). These sections are not considered in the current research due to insufficient data issue. The description of the final four control sections are stated below. Figure 2.5 shows the locations of the final selected sites.

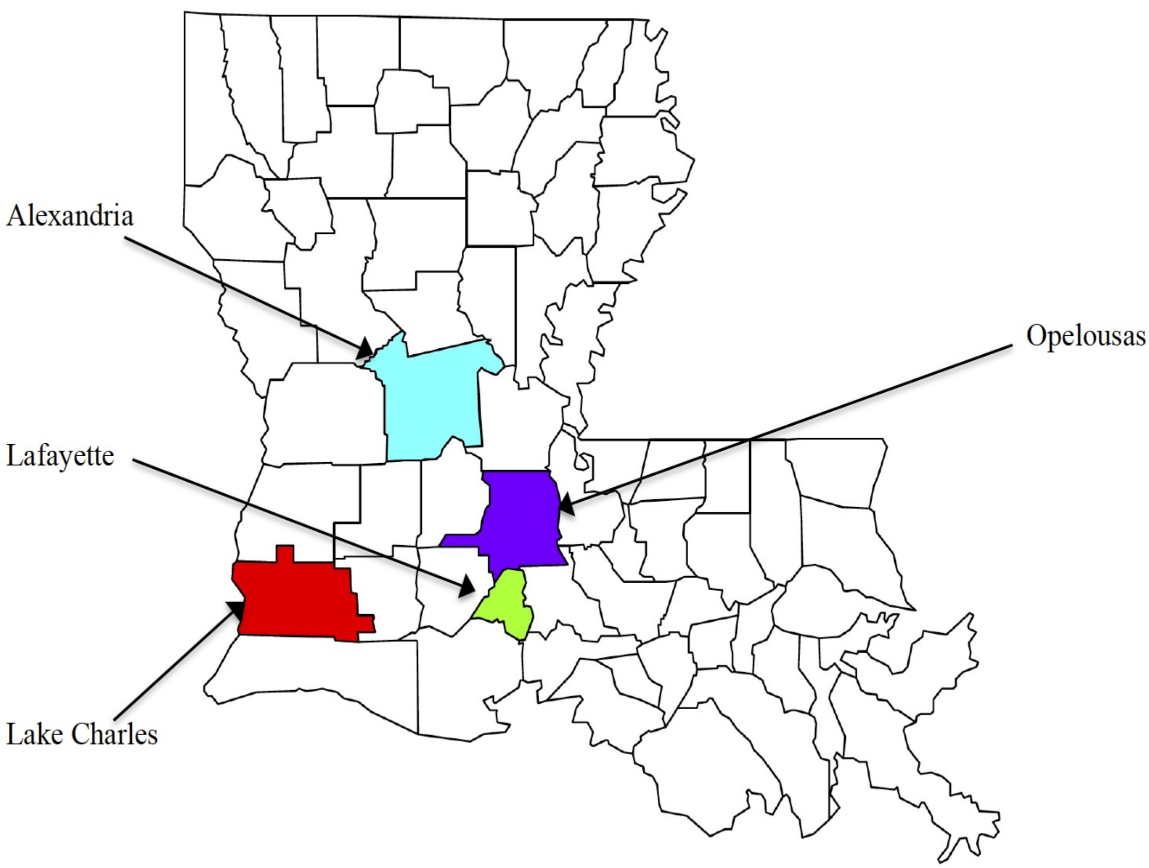

Figure 2.4. Locations of the selected sites

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 AADT around 28,000 in 2009, and the majority of vehicles on the segment are through traffic. There are 14 major driveways connecting to business establishments 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 a constant green light for eastbound through traffic 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 VMT for this roadway segment in the three years prior to the re-striping project were 8.49, 9.90 and 11.74, respectively.

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 a four-lane undivided roadway to a five-lane roadway with a continuous center lane for left-turning vehicles. The layout of the segment and lane configurations before and after the project is shown in Figure 2.5.

Figure 2.5. LA 3025 layout and lane configuration (before and after)

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 a low population density, this segment is under a slightly different environment with an 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 a small retail store, fast food restaurants, and a gas station and residential areas. Three signalized intersections are located within this segment. The layout and lane configuration before and after period for the LA 182 segment is shown in Figure 2.6.

Figure 2.6. LA 182 layout and lane configuration (before and after)

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 miles long (installation year= 2005). It is situated in East in Pineville of Rapides Parish in Alexandria. The

AADTs in the before and after time periods for this segment are very similar. Nearly 45 driveways are connected to various businesses such as fast food restaurants, a gas station, a pharmacy, a shopping center and residential areas. The layout and lane configuration before and after the re-striping project for the LA 28 segment is shown in Figure 2.7.

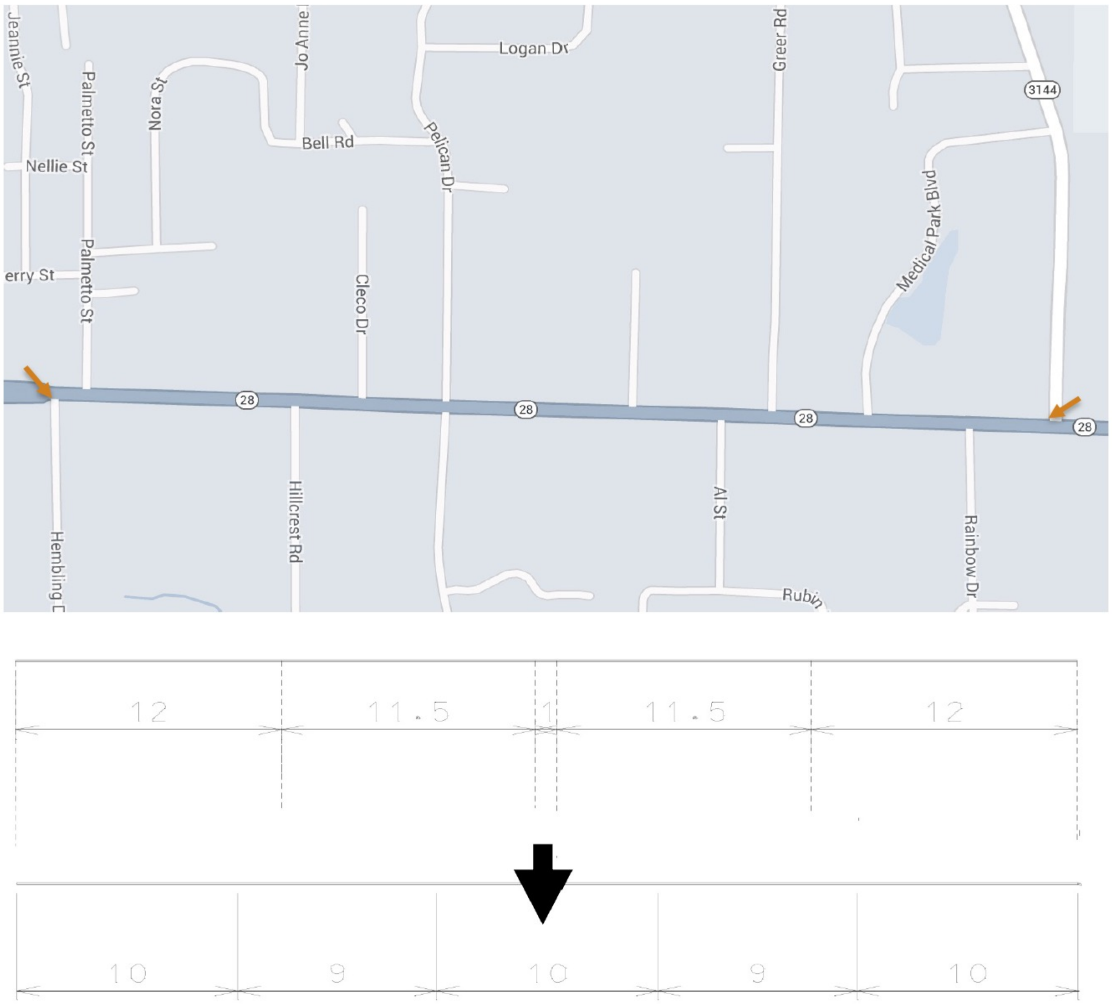

Figure 2.7. LA 28 layout and lane configuration (before and after)

The District 07 office of DOTD also applied a 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 Street and ends at Ryan Street. In 1999, this segment was changed from a four-lane undivided roadway to a five-lane roadway. There is a minor difference in the AADT between the before and after years. Nearly 50 driveways are connected to various businesses such as fast food, shops, a gas station, a pharmacy, a shopping center, an electronics shop, a car rental, and a residential area. The layout before and after the re-striping project on this segment is shown in Figure 2.8.

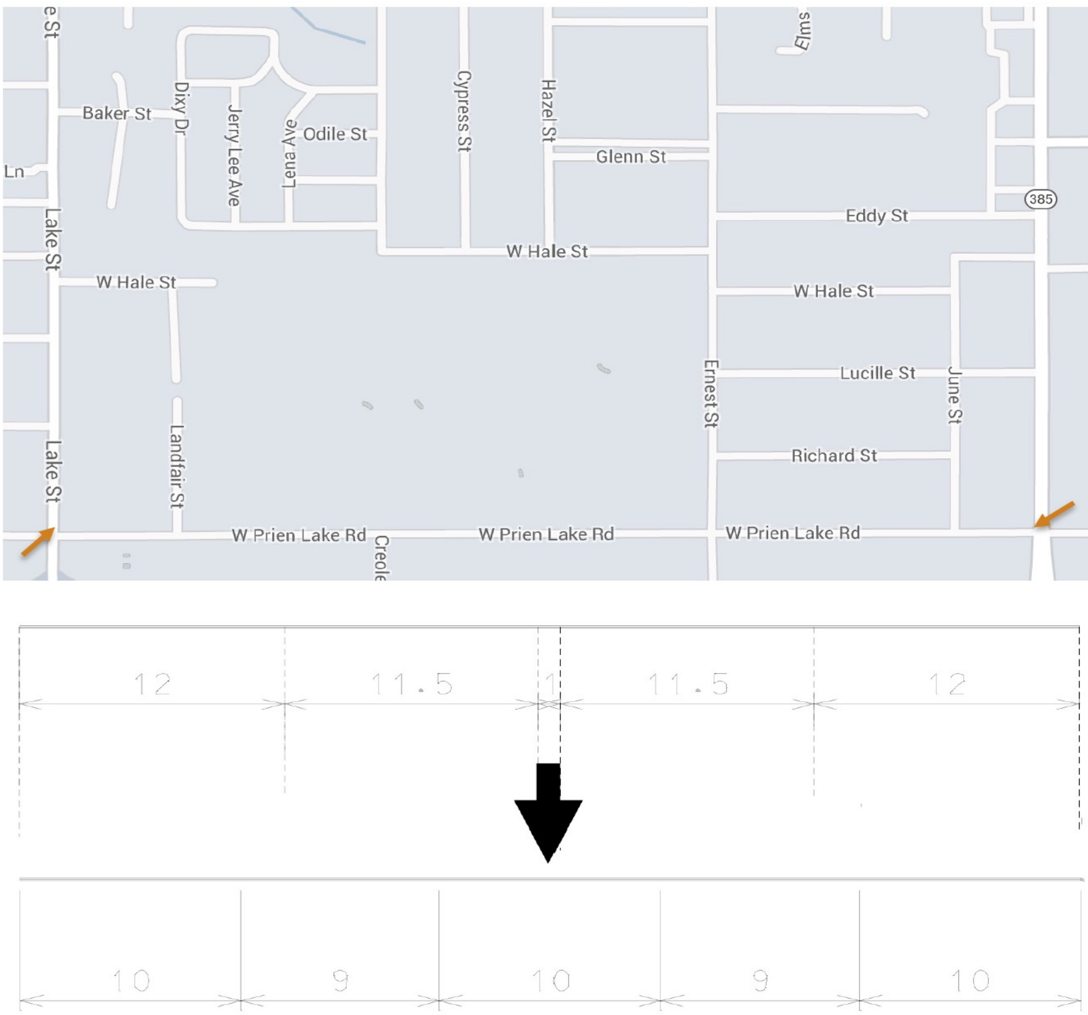

Figure 2.8. LA 1138 layout and lane configuration (before and after)

The number of crashes and the crash rates before and after the re-striping projects for the above four segments are listed in Table 2.2. The speed limit of the roadway segments was almost same in before and after of 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 2.2. Section crashes and crash rates

	Before		After		Percentage Change	
Highway	Crashes	Average Crash Rate	Crashes	Average Crash Rate	Crashes	Average Crash Rate
LA 3025	358	10.05	147	4.59	-59%	-54.30%
LA 182	178	8.12	85	3.53	-52%	-56.50%
LA 28	206	7.38	99	4.09	-52%	-44.60%
LA 1138	260	16.01	167	10.63	-36%	-33.60%

The very impressive results from the four roadways were further analyzed to develop a Crash Modification Factor (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 inconsistencies by police personnel in distinguishing between intersection and access driveway 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.

2.3.2. Before-after Study

Equating safety by simply counting the number of crashes is not the right approach. More specifically, safety can be defined as an expected crash frequency. In other words, safety is considered as the frequency of crashes, by type or severity, expected to occur on the entity during a specified period. 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. In converntional before-after safety studies, two major tasks are done: 1) prediction of what would be the safety of an entity in the after years if treatment had not been applied, and 2) esimation of what would be the safety of an entity in the after years with treatment.

Three methods are widely used in safety literature of before-after studies:

- **Naive Before-after method:** It is the simplest form of before-after study. Only time duration is taken into account.

- **Improved Prediction method:** This method takes into account both time duration and changes of AADT. It is an improved version of the naive before-after studies.

- **Empirical Bayes (EB) method:** Ideal before-after method. 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 (Hauer, 1997). The concepts behind observational studies are shown in Figure 2.9.

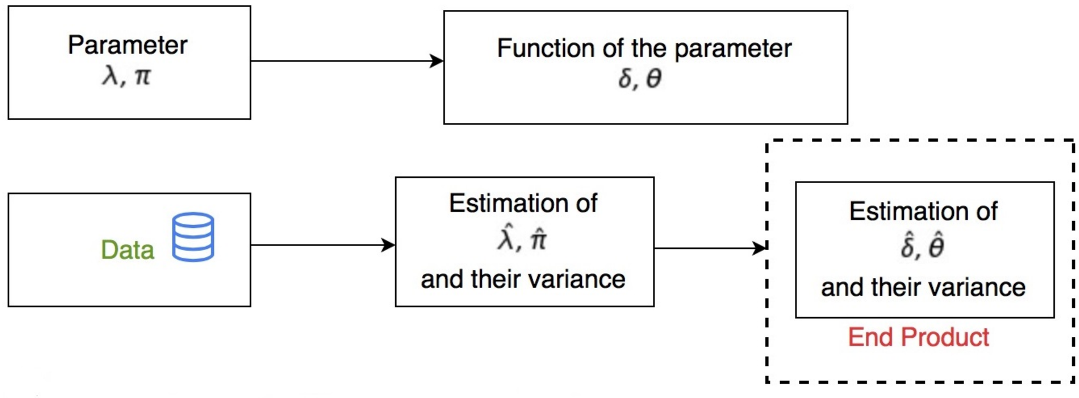

Figure 2.9. Observational before-after study concepts

The details of the safety estimation are summarized as follows:

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

$$\hat{\lambda} = N \tag{2.1}$$

$$\hat{\pi} = \hat{r}_{tf} K \tag{2.2}$$

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

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 both roadways are listed in Table 2.3.

Table 2.3. Safety estimation comparison

Highway	Estimated Crashes with restriping $\hat{\lambda}$	After AADT $\hat{A}_{avg}$	Before AADT $\hat{B}_{avg}$	Ratio $\hat{r}_{tf}$	Estimated Crashes without restriping $\hat{\pi}$
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 of, $\hat{\lambda}$, and $\hat{\pi}$.

$$V\hat{A}R(\hat{\lambda}) = N \tag{2.3}$$

$$V\hat{A}R(\hat{r}_{tf}) = (\hat{r}_{tf})^2 v^2(\hat{A}_{avg} + \hat{B}_{avg}) \tag{2.4}$$

$$V\hat{A}R(\hat{\pi}) = (r_d)^2[(\hat{r}_{tf})^2 K + K^2 var(\hat{r}_{tf})] \tag{2.5}$$

Where,

$V\hat{A}R(\hat{\lambda})$ = Estimated variance of $\hat{\lambda}$

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

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

v = The percent coefficient of variance for AADT estimates

$= 1 + \frac{7.7}{t} + \frac{1650}{AADT^{0.82}}$ [where, t= number of count-days]

$V\hat{A}R(\hat{\pi})$= Estimated variance of $\hat{\pi}$

The results of this application for both roadways are listed in Table 2.4.

Table 2.4. Estimated variance

Highway	Variance of $\hat{\lambda}$, $V\hat{A}R(\hat{\lambda})$	Variance of $\hat{\pi}$, $V\hat{A}R(\hat{\pi})$	Percent co-efficient After, $v(\hat{A}_{avg})$	Percent co-efficient Before, $v(\hat{B}_{avg})$	Variance of $\hat{r}_{tf}$, $V\hat{A}R(\hat{r}_{tf})$
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 difference, $\hat{\delta}$, and safety effectiveness $\hat{\theta}$.

$$\hat{\delta} = \hat{\pi} - \hat{\lambda} \tag{2.6}$$

$$\hat{\theta} = \frac{\frac{\hat{\lambda}}{\hat{\pi}}}{1 + \frac{V\hat{A}R(\hat{\pi})}{(\hat{\pi})^2}} \tag{2.7}$$

Where,

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

$\hat{\theta}$= Estimated unbiased expected crash modification factor for installing edge line

Step Four: Estimating the standard deviation of the crash difference, $\hat{\delta}$, and safety effectiveness $\hat{\theta}$.

$$\hat{\sigma}(\hat{\delta}) = \sqrt{V\hat{A}R(\hat{\lambda}) + V\hat{A}R(\hat{\pi})} \tag{2.8}$$

$$\hat{\sigma}(\hat{\theta}) = \hat{\theta}\frac{\sqrt{\frac{V\hat{A}R(\hat{\lambda})}{(\hat{\lambda})^2} + \frac{V\hat{A}R(\hat{\pi})}{(\hat{\pi})^2}}}{1 + \frac{V\hat{A}R(\hat{\pi})}{(\hat{\pi})^2}} \tag{2.9}$$

Where,

$\hat{\sigma}(\hat{\delta})$= Standard deviation of $\hat{\delta}$

$\hat{\sigma}(\hat{\theta})$= Standard deviation of $\hat{\theta}$

The value of $E(\hat{\theta})$ can be written as: $E(\hat{\theta})$=$\frac{\lambda}{\pi} + [0 \times VAR(\hat{\lambda}) + 2\frac{\lambda}{\pi}VAR(\hat{\pi})]/2$. It can also be written as $E(\hat{\theta}) = \frac{\lambda}{\mu}[1 + VAR(\hat{\pi})/\pi^2]$. It appears that if I estimate θ by $\hat{\lambda}/\hat{\pi}$, the mean of the estimates would be larger than λ/π by $[1 + VAR(\hat{\pi})/\pi^2]$. To get the estimator unbiased, I need to divide it by $[1 + VAR(\hat{\pi})/\pi^2]$.

The results of Step Three and Step Four are listed in Table 2.5.

Table 2.5. Estimated safety impact

Highway	Estimated safety impact of the project, $\hat{\delta}$	Estimated CMF, $\hat{\theta}$	Standard Deviation of $\hat{\delta}$, $\hat{\sigma}(\hat{\delta})$	Standard Deviation of $\hat{\theta}$, $\hat{\sigma}(\hat{\theta})$
LA 3025	175	0.45	27.62	0.051
LA 182	110	0.43	20.53	0.062
LA 28	111	0.47	21.28	0.062
LA 1138	87	0.65	25.42	0.042

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 CMFs are 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, respectively.

2.3.3. Crash Characteristics

Exploratory Data Analysis (EDA) is an approach for data analysis that employs a variety of methods, mostly graphical, to look at the data more intuitively. I have conducted EDA on the dataset for further exploration. The biggest concern over 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 2.10, rear-end crashes did decrease by 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 a decreasing trend. On LA 182, there were 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.

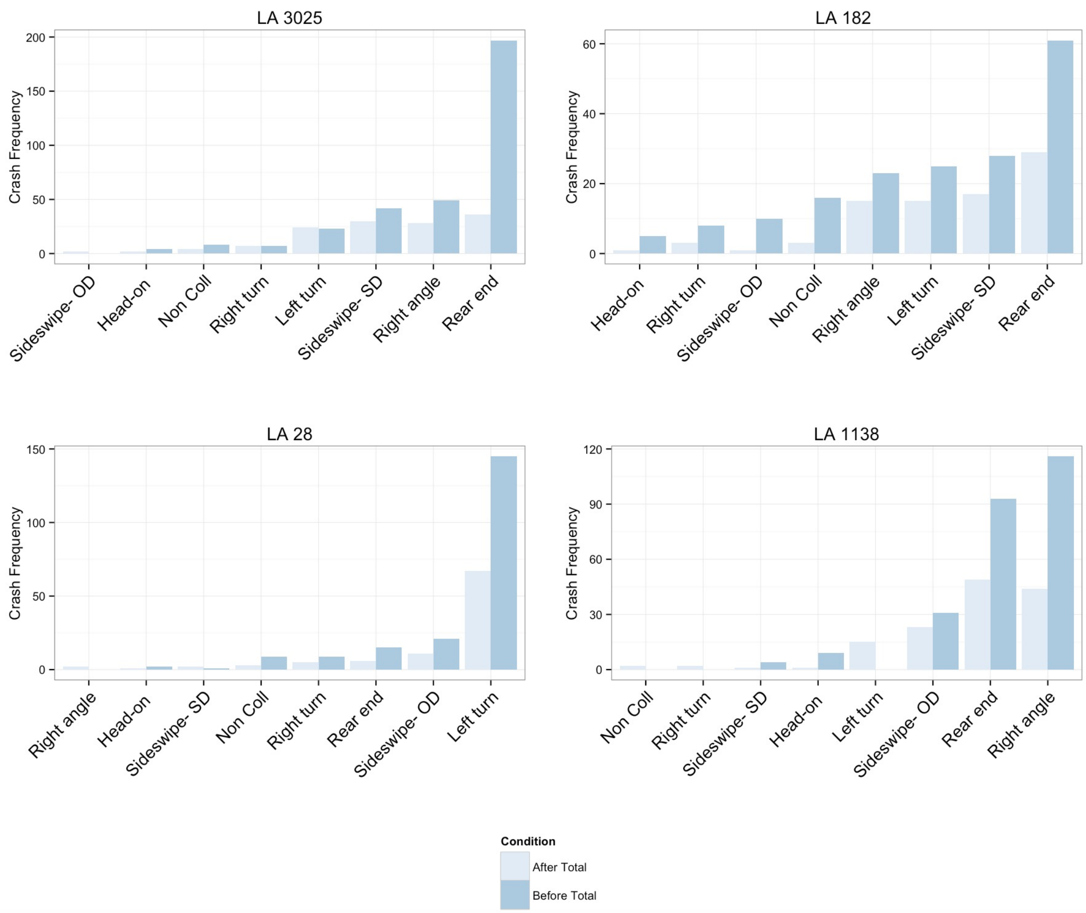

Figure 2.10. Different types of traffic collisions

The crashes by pavement surface conditions and time of day were also investigated from the before and after periods. As shown in Figure 2.11, 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 conditions, the reduction is , 82% for LA 3025 , 58% for LA 182, 74% for LA 28, and 33% on LA 1138.

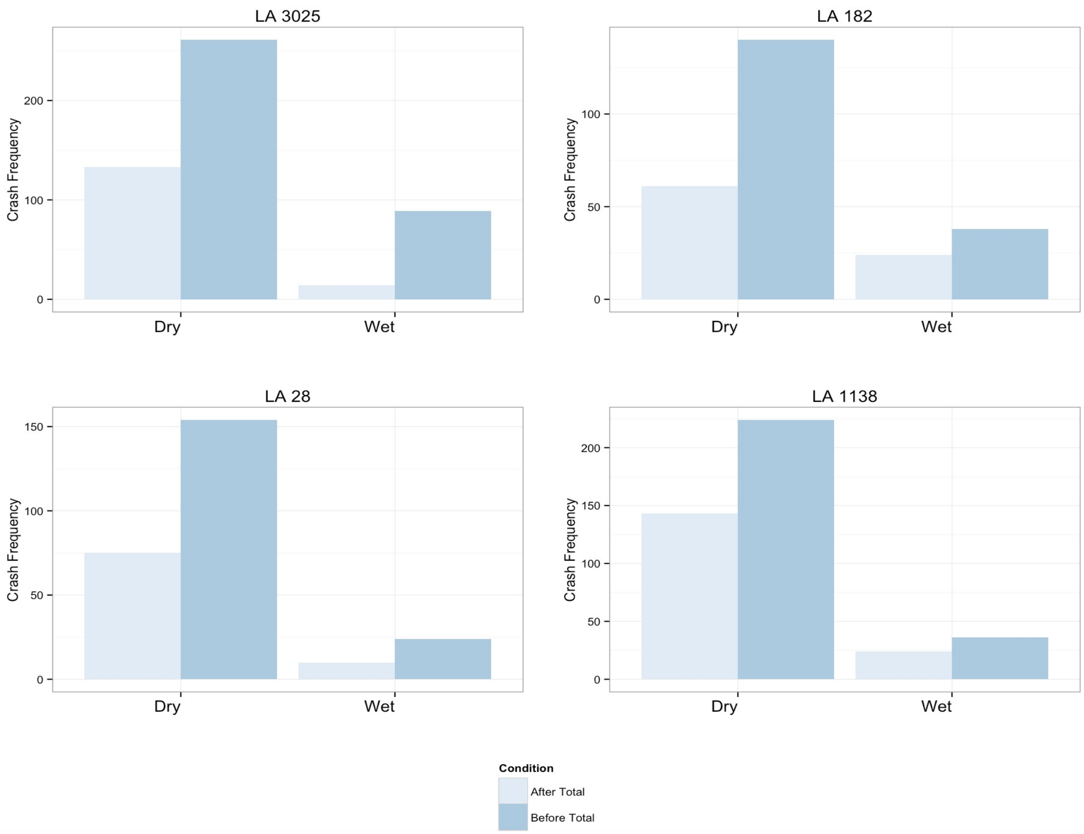

Figure 2.11. Crashes in different pavement surface condition

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 2.12.

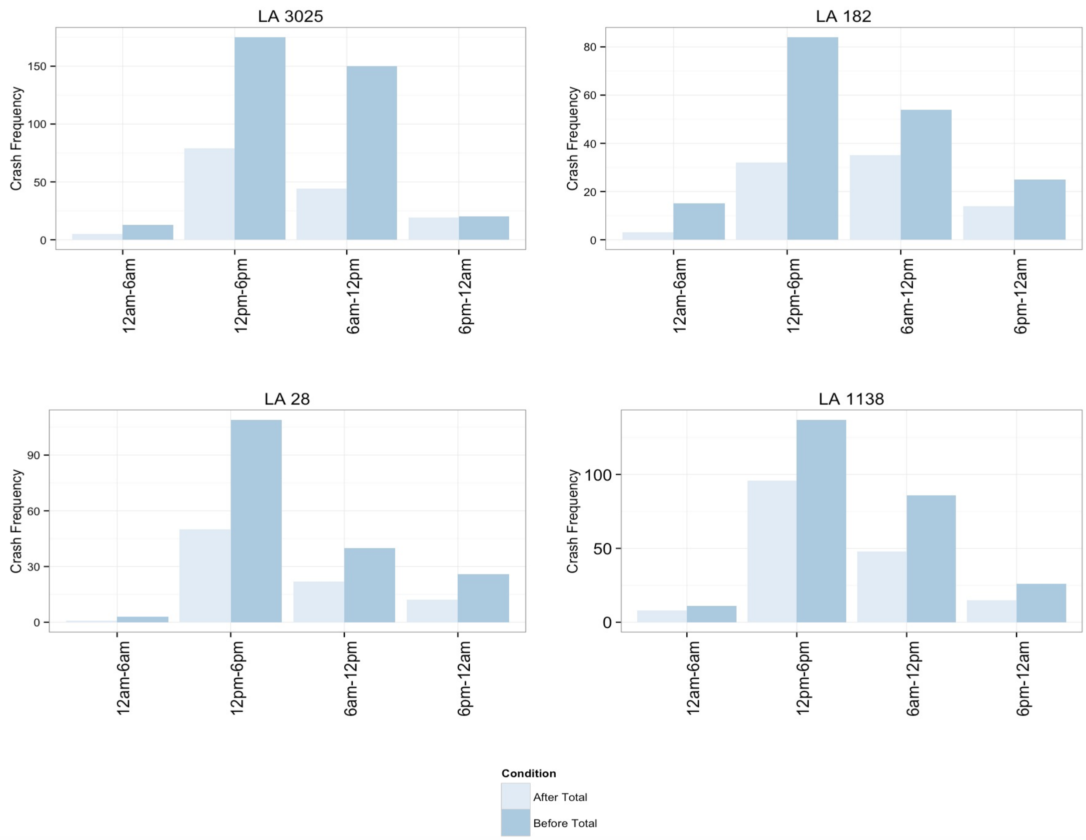

Figure 2.12. Crashes in different time of day

2.4. Lane Conversion in HSM

Figures 2.13 and 2.14 Chapter 12 of the HSM illustrates the relationship between AADT and predicted average crash frequency per mile for 5 different urban roadway types, i.e., 5T for five-lane roadways with a middle lane for left turns, 4U for four-lane undivided roadway, 2U for two-lane roadway, 4D for four-lane divided roadway, and 3T for three-lane roadway with middle-lane for left-turns. Five-lane undivided roadways have the highest crash frequencies at all AADT levels, as shown below.

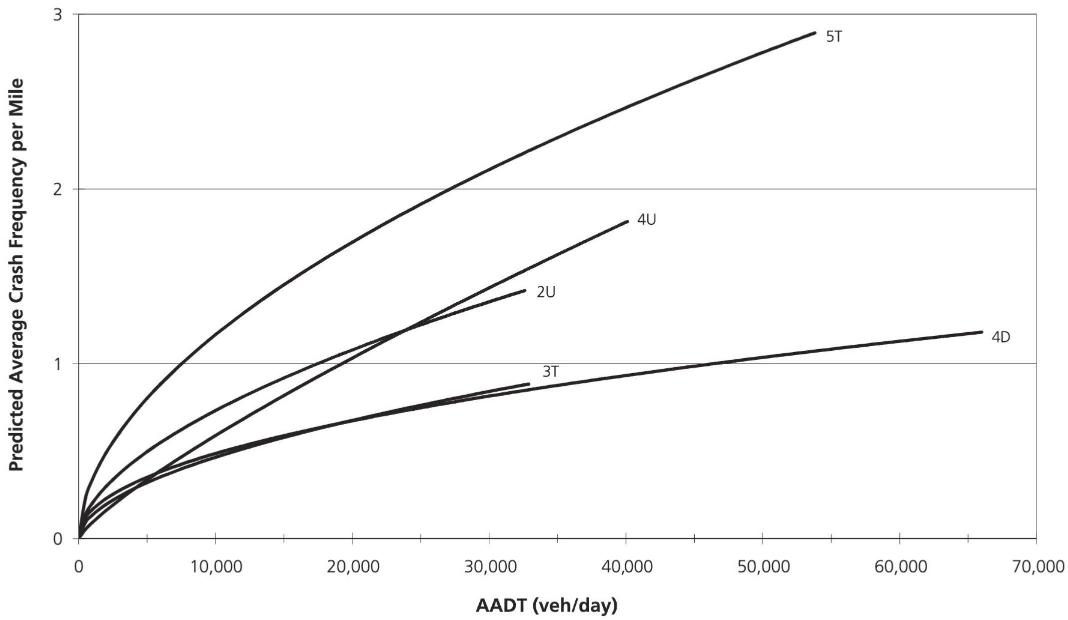

Figure 2.13. Safety Performance Function (SPF) for ROR crashes

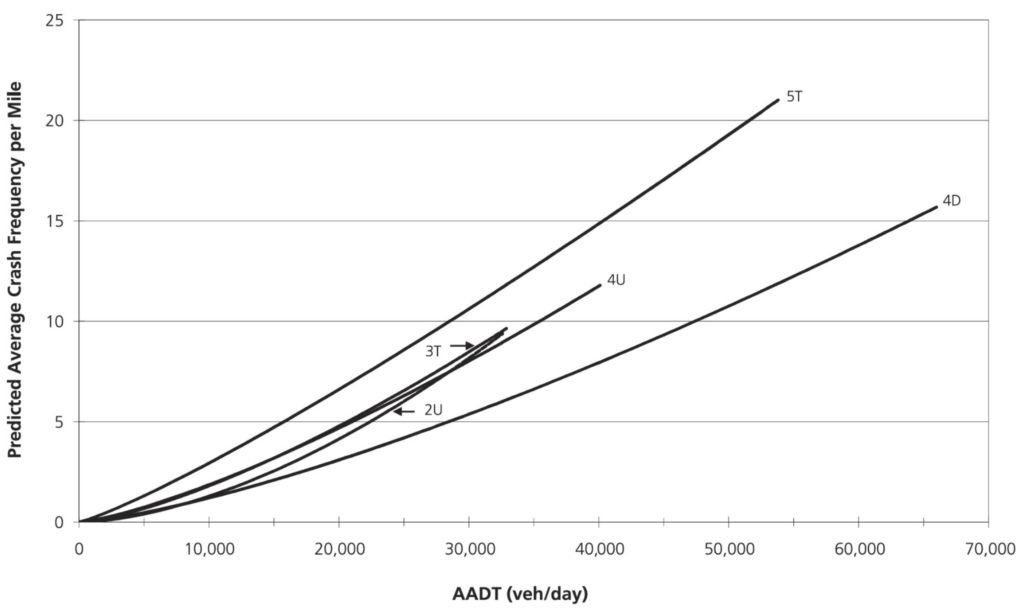

Figure 2.14. SPF graphics for multiple vehicle non-driveway collisions

In the urban arterial street mode, the predicted average crash frequency is calculated by five crash types, namely: multiple-vehicle non-driveway collisions, single-vehicle crashes, multiple-vehicle driveway-related collisions, vehicle-pedestrian collisions, and vehicle-bicycle collisions.

The relationship between AADT and multiple-vehicle driveway-related collisions is calculated and shown in Figure 2.15 with four different numbers of driveways, which are not given in Chapter 12.

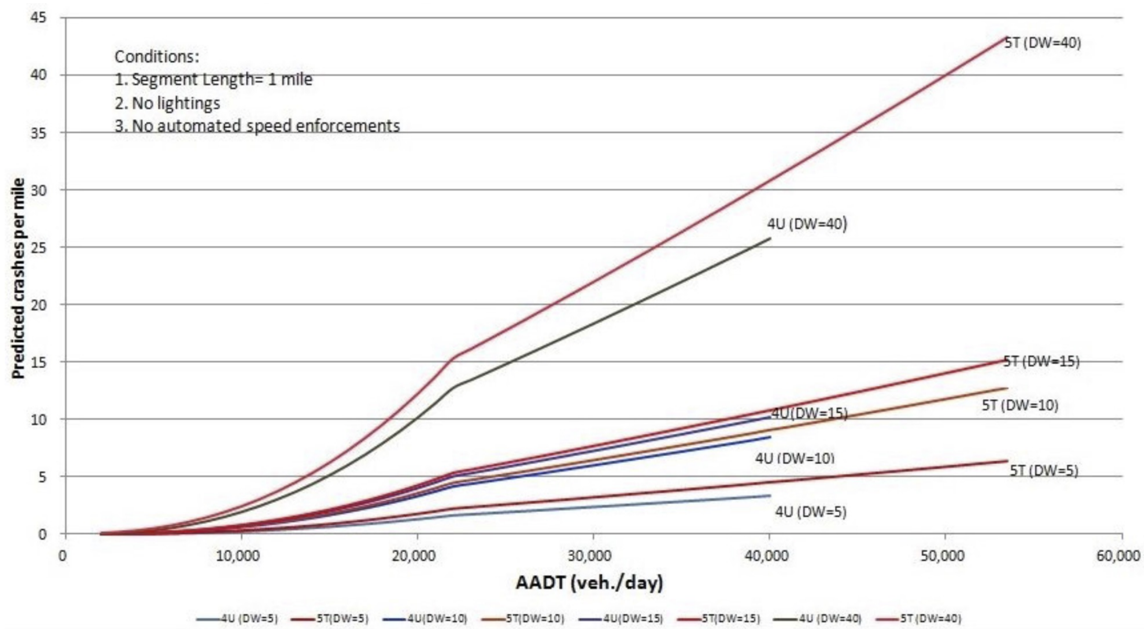

Figure 2.15. Multiple-vehicle driveway-related predicted crashes per mile

For all three figures shown under the same condition (except AADT), five-lane undivided consistently yields higher predicted average crashes (or expected crashes). Although the difference in each chart (one crash type) is small, the total is not.

The literature review indicates that five-lane undivided is generally safer than four-lane undivided on urban settings, and our recent study on four urban arterial streets in Louisiana further confirmed this fact. After re-striping projects, annual crashes on both streets (20 miles apart with around 30,000) have dropped about 50% consistently for seven years.

2.5. Discussion of Results

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, I have found more evidence of its effectiveness. Figure 2.16 shows the crash reduction on LA 3025 to be sustainable, which further confirms the effectiveness of the crash countermeasure. Even a segment experienced a 10% increase in the AADT from the 2004-2006 to 2008-2010.

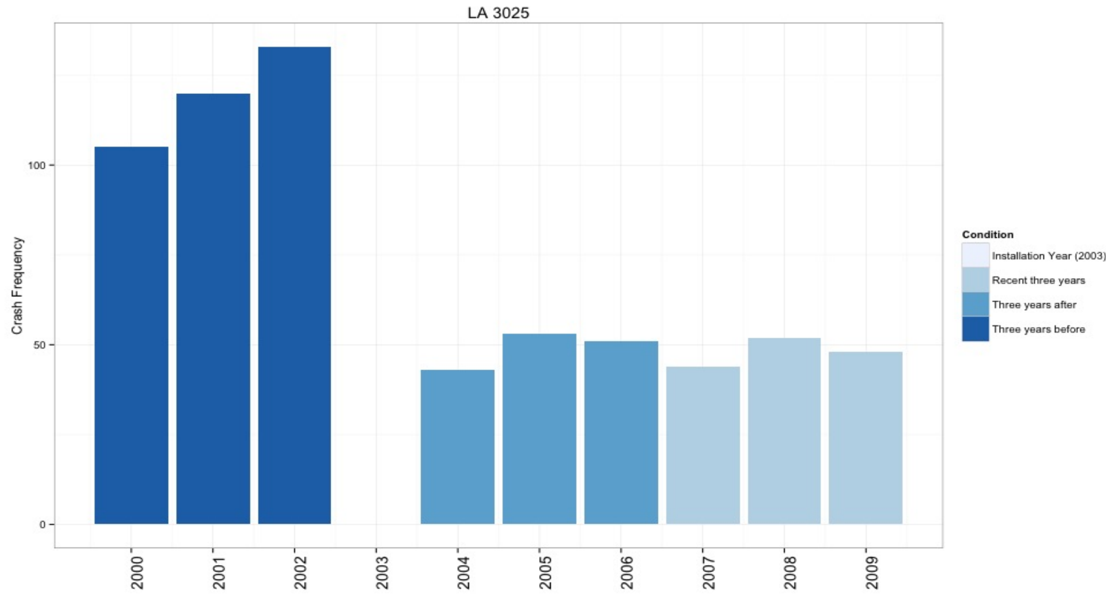

Figure 2.16. LA 3025 recent year crash trends

Lastly, the distribution of crash severity before and after the re-striping projects is examined. As shown in Table 2.6, crash frequencies decreased for both 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 2.6. Crash severity statistics

	LA 3025			LA 182			LA 28			LA 1138		
Crash Severity Type	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%
Fatal Crashes	0	2	increase	0	0	0%	0	0	0%	0	0	0%
Injury Crashes	81	40	-50.6%	54	22	-59.3%	58	23	-60.3%	88	48	-45.4%
PDO Crashes	277	105	-62.1%	124	63	-49.2%	148	76	-48.7%	172	119	-30.8%

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 [18], the average cost for an injury crash is $53,676, and for a PDO is $3,216; this yields a benefit to cost (B/C) ratio of 166 for the LA 182 segment if using an outside contract (assuming the paint lasts about three years). This is the most conservative B/C ratio: it would be larger if in-house maintenance crew costs were used. The benefit-cost ratios for all four segments is shown in Table 2.7.

Table 2.7. Benefit-cost ratios

Control Section	**Total Benefits (in USD)**	**Total Cost (in USD)**	**Benefit-Cost 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 3025	2,317,488	12,300	188

2.6. Conclusions

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 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 four 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 paid not only to the driveway or access point density but also to 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 businesses 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 25 years ago. The Minnesota document lists the crash rate is 6.75 for four-lane undivided roadways and 4.01 for five-lane roadways with a center turn lane. In the NCHRP report, it states that conversion from a four-lane undivided cross section to a five-lane TWLTL cross section with narrower lanes reduced crash rates, on the average, by 45%. This study shows higher than 50% in crash reductions. However, the application experiments with the two models from the Chapter 12 of HSM yield the opposite conclusion. That is, under exactly the same conditions, the calculated expected crashes are higher on five-lane roadway than on four-lane undivided roadways, which may show a need for improvement on the next edition of the HSM.

CHAPTER 3: INVESTIGATING SAFETY IMPACT OF EDGE LINE ON NARROW RURAL TWO-LANE HIGHWAYS BY EMPIRICAL BAYES METHOD

Abstract

Narrow, rural two-lane highways are mostly characterized by low design features, light traffic volumes with high crash rates and particularly high fatal crash rates. There are about 5,000 miles of narrow, rural two-lane highways administrated by the DOTD. Run-off-road (ROR) crashes are the most common type of crashes on narrow, rural two-lane highways. As its not required by the Manual on Uniform Traffic Control Devices (MUTCD), many highways of this type do not have edge lines because of their low traffic volumes. There are two main concerns for edge line implementation on narrow two-lane highways: (1) the potential increase in head-on collisions, and (2) added maintenance cost to the already constrained annual maintenance budget. This paper introduces the second part of a study that evaluates the safety impact of edge lines on narrow, rural two-lane highways in Louisiana. The first part of the study proved that edge lines centralize the lateral position of vehicles based on the data collected from 10 locations. This second part of the edge line study evaluates the safety performance before and after the implementation of edge lines from roadway segments selected from all DOTD districts. By using the Empirical Bayes (EB) method, the study shows that edge line implementation significantly reduces expected crash frequencies. While reducing ROR crashes, edge line implementation also reduces head-on crashes. It is interesting to note that the implementation of edge lines benefits primarily male drivers and young drivers. Because of the crash decreasing trend observed in the three year period that is classified as the after time period in the study, the final estimated CMF is 0.85 with a standard deviation of

0.039. The very high benefit-cost ratio strongly supports the idea of edge line implementation on narrow, rural two-lane highways in Louisiana.

3.1. Introduction

Improving highway safety is a critical issue facing DOTD because traffic fatality rate (fatalities per 100 million vehicle miles traveled) of Louisiana has been consistently higher than the national average despite the improvements made in the last several years. In 2011, the national average fatality rate was 1.0 while Louisiana had 1.12. Road departure crashes are the most common type of crashes on two-lane highways, particularly on narrow, rural two-lane highways. Narrow, rural two-lane highways are generally characterized by low design features and light traffic volumes.

In 2010, there were 12,467 crashes on rural two-lane highways in Louisiana. Approximately 34% of fatal crashes and 35% of fatalities occurred on rural two-lane highways in that same year. Running-off-roadway or roadway departure crashes are the most common type of crashes on narrow two-lane highways, which account for approximately 60% of total crashes. Pavement marking is considered an inexpensive crash countermeasure to reduce roadway departure crashes since it provides a visual guidance that helps confine vehicles within the travel lane. The MUTCD provides guidelines for the installation of edge lines. However, rural two-lane highways with narrow lane widths are not always required to have edge lines due to their low daily traffic volumes. While debating whether edge lines should be implemented on all rural two-lane highways to enhance roadway safety regardless of its lane width or AADT, the state engineers had two concerns in particular. One of the concerns was that the presence of edge lines may influence drivers to operate closer to the centerline thus increasing the risks of head-on and sideswipe crashes. The other concern was that the benefits of implementing edge lines would not be worth the added maintenance cost to an already constrained maintenance budget. To investigate the impact of edge lines, Louisiana Transportation Research Center (LTRC) sponsored a study in 2005 investigating the vehicular lateral position before and after the edge line installation (Sun and Tekell, 2005). Based on the data collected on 10 segments from DOTD District 3, the investigation essentially concluded that:

- With edge lines, centralization of a vehicles position is more apparent during nighttime, which reduces the risk of 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.

To answer the question on how much crashes can actually be reduced by edge lines on narrow, rural two-lane highways, the second part of the study was conducted with as focus on the crash analysis before and after edge line implementation. To investigate the financial feasibility of the edge line implementation, the benefit-cost analysis was also performed as part of the second study.

3.2. Literature Review

Pavement markings have traditionally been viewed by various transportation agencies as an inexpensive crash countermeasure. Unlike other types of potential crash countermeasures, there have 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 into three main categories: lateral position of the travelling vehicle, crash reduction, and benefit-cost analysis.

The earliest study on vehicle position was actually conducted in Louisiana by Thomas in 1958 on a 24-ft. rural two-lane highway in the state. 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 (Thomas, 1958). In 1960, the same author repeated the study at different locations in Louisiana, which yielded almost the same conclusion (Thomas and Taylor, 1960). Other similar studies on the vehicular lateral position were conducted by the Missouri State Highway Department in 1969 and Hassan in 1971 (MIS, 1969; Hassan, 1971). These two studies again gave similar conclusions. In 2000, research conducted by Steyvers et al. in The Netherlands employed video recording apparatus 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. (Steyvers and De Waard, 2000). It was concluded that edge-lines would provide a simple and effective way of inducing a more favorable lateral position on rural roads. Musick adopted 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 exposed that edge line placement resulted in a considerable reduction in fatal and injury crashes (Musick, 1960). A before and after study identified that edge line placement contributed nearly a 20% reduction in crashes. Basile found a similar trend to Musicks study when he conducted a before and after analysis on the highways of Kansas

In a 2005 study, Tsyganov et al. employed crash data from the Texas Department of Public Safety to evaluate the current relationship between highways with and without edge lines (Tsyganov et al., 2005). The results concluded that the expected crash reduction would be nearly 26%, and the best safety benefit was observed on horizontal curves and on highways with pavement widths of 18 to 20 ft. A study completed in 1991 by Miller quantified the benefit-cost ratios of edge lines for different roadway conditions (Miller, 1992). Analyzed crash data determined that pavement markings contributed a 60:1 benefit-cost ratio.

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 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 (Hughes et al., 1989). Cottrells study in 1987 can be considered as one of the earliest safety evaluations of wider edge lines (Cottrell Jr, 1986). The result presented nearly a 14% reduction in both ROR and opposite-direction (OD) crashes.

Another study, from New Mexico by Hall, used 530 miles of rural two-lane highways (those having high crash rates) to estimate the edge line impact on ROR and OD crash rates (Hall, 1987). The findings exhibited that crash rates decreased approximately 10% at the treatment locations and 16% at the comparison sections. A recent 2010 study by Miles et al. evaluated the potential benefits of using wider and brighter edge line markings (Miles et al., 2010). The results showed that safety improvement is positive after the use of wider edge lines for two-lane highways.

In the first edition of the HSM, there are CMFs for placing standard and wide edge line markings on rural two-lane highways (without mentioning the width of pavement) (AAS, 2010). The CMF value of the edge line placement from the HSM is within the range of 0.90 to 1.10. Although few investigations were conducted on the effectiveness of edge line implementation more than two decades ago, no studies have been conducted on edge lines in rural narrow two-lane highways with light daily traffic volume.

3.3. What is an Edge line?

Edge lines are longitudinal pavement markings that mark the outer edge of a roadway. The purpose of edge lines is to provide drivers with a visual guidance to help them keep their vehicles in a safe position within a travel lane. Edge lines are extremely helpful for curve recognition, curvature perception, and reduction of lateral variability. Discontinuities in an edge line give the drivers visual aid in recognizing upcoming intersections, and driveways.

3.4. Data Collection

As displayed in Figure 3.1, about 40% of total rural two-lane roadway mileage under DOTD has a pavement width of less than 22 feet and carries less than 20% of VMT. Rural two-lane highway segments with pavement width less than 22 feet were selected from all DOTD districts. Because of their low AADT, these sections did not have and are not required by MUTCD to have pavement edge lines.

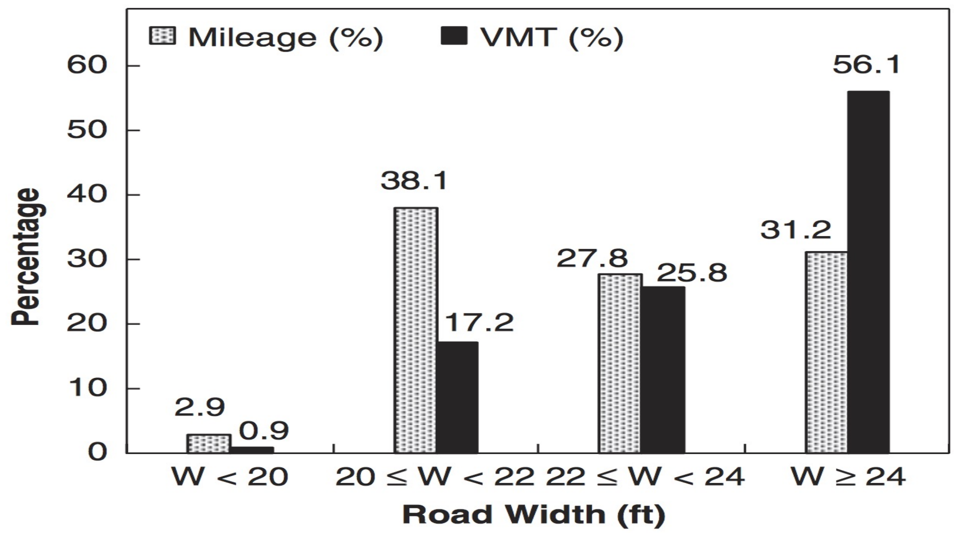

Figure 3.1. Density of AADT in before-after study

After the initial segment selection, I verified each segment by reviewing images from the DOTD biennial pavement condition survey since changes do occur each year on roadway segments such as pavement widening and upgrading to multilane highways. These changes are not always updated in time for the database. After eliminating a few segments because they are either on a bridge or were upgraded to a wider lane width, the final selection was made as shown in Table 3.1. These segments vary in length following the DOTD highway segmentation system to ensure that the most important attributes such as pavement type and width, and shoulder type and width are uniform within each segment.

Table 3.1. Summary of segments selected for edge line implementation

DOTD District No.	Total Length (in Mile)	Number of Roadway Segments
2	1.38	1
3	31.96	9
4	6.06	2
5	24.75	4
7	12.51	2
8	4.84	2
58	1.17	1
61	7.85	3
62	19.12	4
Total	109.64	28

Edge lines were implemented on the selected segments between March and June of 2008 by each DOTD district and were verified by the site-visits (nearly 64%) during the 2008 summer or by the imaging review. The crash data used in the analysis is from 2005 to 2011, i.e., three years before (2005-2007) and three years after (2009-2011) the edge line implementation. The conversion from no edge line to edge line installation is shown in Figure 3.2.

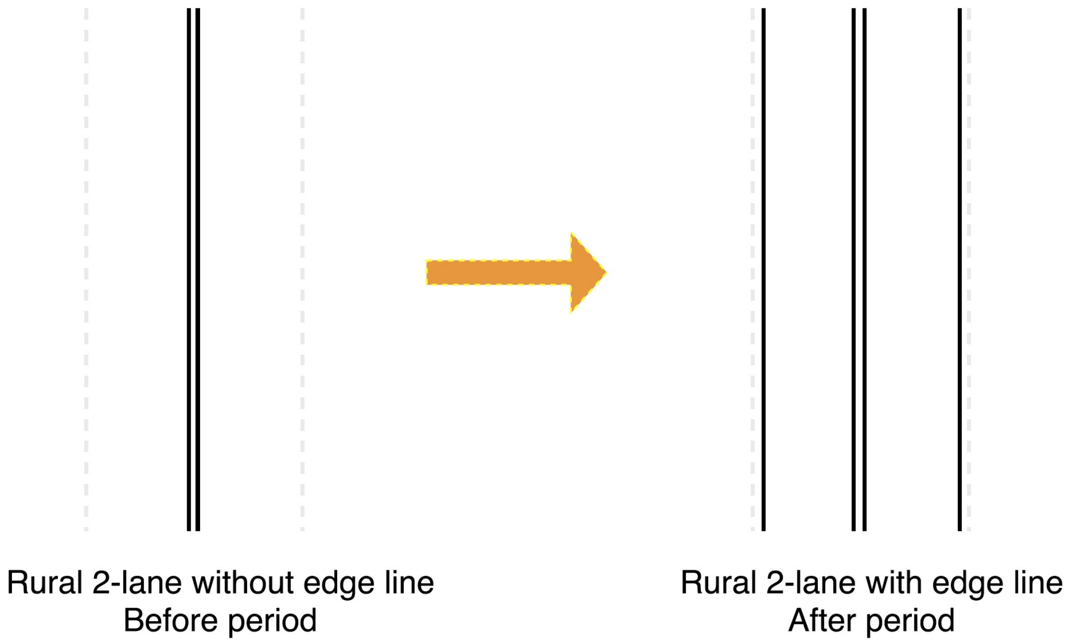

Figure 3.2. Before-after roadway condition (rural two-lane)

3.4.1. Before-after Study

In observational studies, there remains a link between countermeasure implementation and past crash records. This link occasionally heads towards the selection bias or regression-to-mean (RTM) bias. In this study, the EB method is used to estimate the impact of edge lines, which combines the observed crash frequency with the predicted crash frequency to estimate the expected change in crashes. This method accounts for the effect of RTM, changes in traffic volume and potential other potential changes in roadway features during the before and after time periods. It addresses two problems of safety estimation; it increases the precision of estimates, and it corrects for the RTM bias. The increase in precision is useful when the usual estimate is too imprecise for use. The elimination of the RTM bias helps in dealing with crash history of the countermeasure connected with the reason why its safety is estimated. This method is considered to be a statistically defensible method for safety evaluation (Hauer, 1997). Specifically, this method estimates safety effectiveness by examining the difference between observed crashes in the after time period and the expected crashes had treatments not been applied. The Safety Performance Function (SPF) is an equation giving an estimate of crashes as a function of some trait values (e.g., AADT, lane width) and of other important regression parameters. SPFs are calibrated from data by statistical methods. In the calibration it is usually assumed that the crash counts which serve as data come from a negative binomial distribution. One of the parameters of this distribution is the over dispersion parameter. The SPF for rural two-lane highways from the first edition of HSM was used in this study. The basic EB calculation steps are described below.

Step One: Estimating the expected crashes before and after the edge line implementation by the SPF.

$$\hat{E}(k_{iy}) = AADT \times L_i \times 365 \times 10^{-6} \times e^{(-0.312)} \times \prod_{j=1}^{n} CMF_j \tag{3.1}$$

Where,

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

L_i= length of roadway segment i (mi)

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

The summation of the SPF estimates on segment i over three before, P_i, and three years after, Q_i, are:

$$P_i = \sum_{y=1}^{3} \hat{E}(k_{iy}) \tag{3.2}$$

$$Q_i = \sum_{y=5}^{7} \hat{E}(k_{iy}) \tag{3.3}$$

The ratio of the SPF estimates before and after edge line implementation for segment i is:

$$C_i = \frac{\sum_{y=5}^{7} \hat{E}(k_{iy})}{\sum_{y=1}^{3} \hat{E}(k_{iy})} = \frac{Q_i}{P_i} \tag{3.4}$$

Step Two: Estimating the expected number of crashes with EB method, M_i, before edge line implementation and variance of M_i.

$$M_i = w_i P_i + (1 - w_i) K_i \tag{3.5}$$

$$w_i = \frac{1}{1 + kP_i} \tag{3.6}$$

$$k = \frac{0.236}{L} \tag{3.7}$$

Where,

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

w_i= weight factor

k= over dispersion parameter of the negative binomial regression model

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

An estimated variance of M_i is given by:

$$var(M_i) = (1 - w_i) M_i \tag{3.8}$$

$$\hat{M} = \sum_{i=1}^{I} M_i \tag{3.9}$$

$$v\hat{a}r(\hat{M}) = \sum_{i=1}^{I} var(M_i) \tag{3.10}$$

Where,

$\hat{M}$= sum of the expected number of crashes, M_i, before edge line implementation

$v\hat{a}r(\hat{M})$= estimated variance of $\hat{M}$

I= total number of selected sites for edge line implementation

Step Three: Estimating the EB predicted crashes for the after time period and its variance.

$$\hat{\pi}_i = C_i M_i \tag{3.11}$$

$$v\hat{a}r(\hat{\pi}_i) = C_i^2 v\hat{a}r(M_i) = C_i^2(1 - w_i)M_i \tag{3.12}$$

$$\hat{\pi} = \sum_{i=1}^{I} \hat{\pi}_i \tag{3.13}$$

$$v\hat{a}r(\hat{\pi}) = \sum_{i=1}^{I} var(\hat{\pi}_i) \tag{3.14}$$

Where,

$\hat{\pi}_i$= estimate of EB predicted crashes

Step Four: Estimating the index of effectiveness of the edge line, $\hat{\theta}$, and its variance.

$$\hat{\theta} = \frac{L}{\hat{\pi}[1 + \frac{v\hat{a}r(\hat{\pi})}{\hat{\pi}^2}]} \tag{3.15}$$

$$sd(\hat{\theta}) = \frac{\hat{\theta} \times \sqrt{\frac{1}{L} + \frac{v\hat{a}r(\hat{\pi})}{\hat{\pi}^2}}}{1 + \frac{v\hat{a}r(\hat{\pi})}{\hat{\pi}^2}} \tag{3.16}$$

Where,

L= total observed crash counts from the after time period

Note that the calibration parameter introduced in Chapter 10 of the HSM is not used in the calculation since it is canceled in equation (3.4) for the ratio calculation. The results are listed in Table 3.2. The effectiveness index for the edge line implementation is estimated as 0.84 with a standard deviation of 0.04.

Table 3.2. Empirical Bayes results

DOTD District	Section Length	No. of Control Section	L_i	Safety Effectiveness, $\hat{\theta}$	$\hat{\sigma}(\hat{\theta})$	$\hat{\theta} + 3 \times \hat{\sigma}(\hat{\theta})$	$\hat{\theta} - 3 \times \hat{\sigma}(\hat{\theta})$
2	1.38	1	7	0.45	0.1975	1.04	-0.15
3	31.96	9	234	1.13	0.1069	1.45	0.82
4	6.06	2	23	0.56	0.1459	0.99	0.12
5	24.75	4	261	0.99	0.0894	1.26	0.73
7	12.51	2	41	0.74	0.1459	1.17	0.3
8	4.84	2	33	0.72	0.1612	1.2	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

3.5. Exploratory Data Analysis

3.5.1. Traffic Flow Characteristics

In addition to the CMF development, traffic characteristics were also analyzed to see if there are significant changes between the before and after time periods. It is noted that the AADT increased by 4% on average during the after period. The density plot of AADT is presented in Figure 3.3, which indicates two spikes in AADT during the after period. Figure 3.4 represents the density plot of estimated operating speed in before-after periods, which shows densities of the moderate speed (50-65 mph) increased in the after years. Edge lines helped the drivers keep their vehicles in the proper lane; at the same time, drivers increased the speed because of the nature of behavioral adaptation. Because drivers usually feel confidence in driving with more speed with a visual guidance. The box and whisker plot in Figure 3.5 clearly shows the increased average speed.

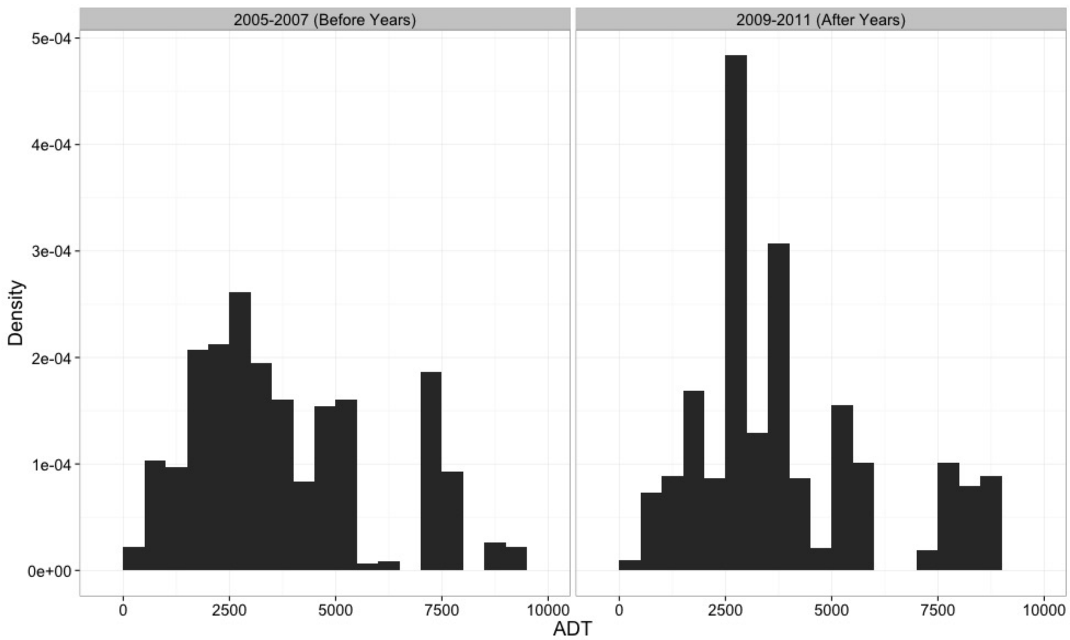

Figure 3.3. Density of AADT in before-after study

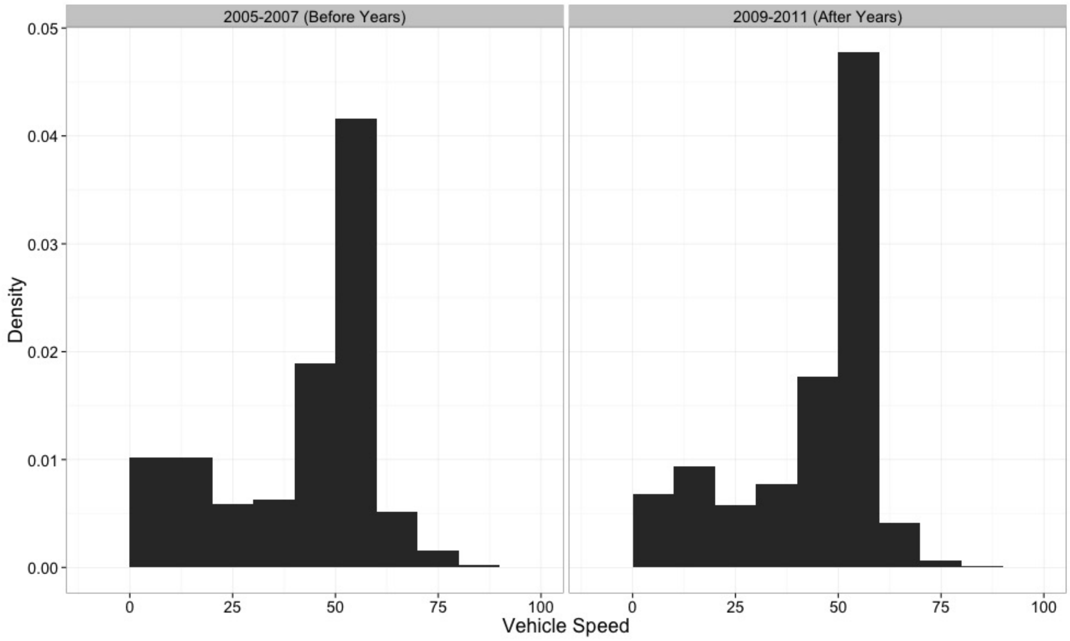

Figure 3.4. Density of estimated speed of the vehicles in before-after periods

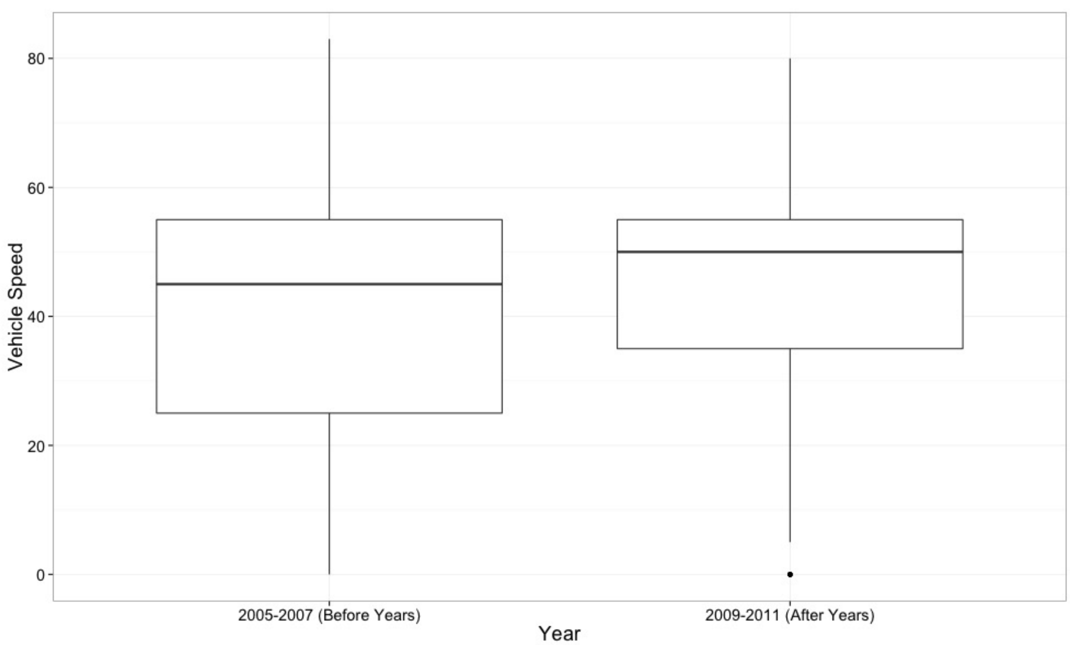

Figure 3.5. Box and whisker plot of estimated speed of the vehicles

Figure 3.6 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 in the after periods.

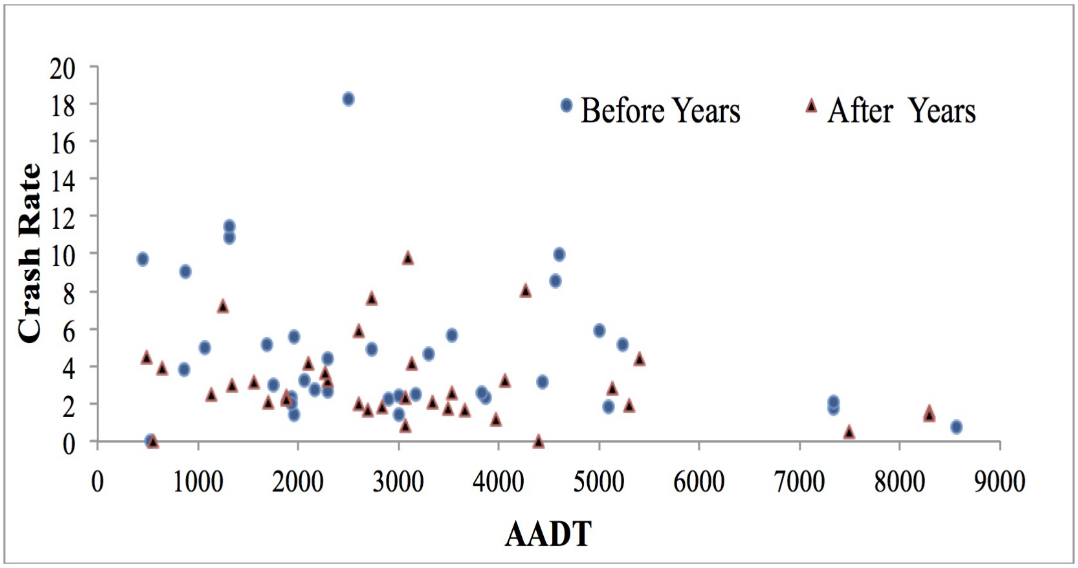

Figure 3.6. AADT vs. crash rate in before-after periods

3.5.2. Crash Characteristics

In addition to the change in traffic characteristics, researchers also investigated the change in crash characteristics. Figure 3.7 shows the crash severities by year.

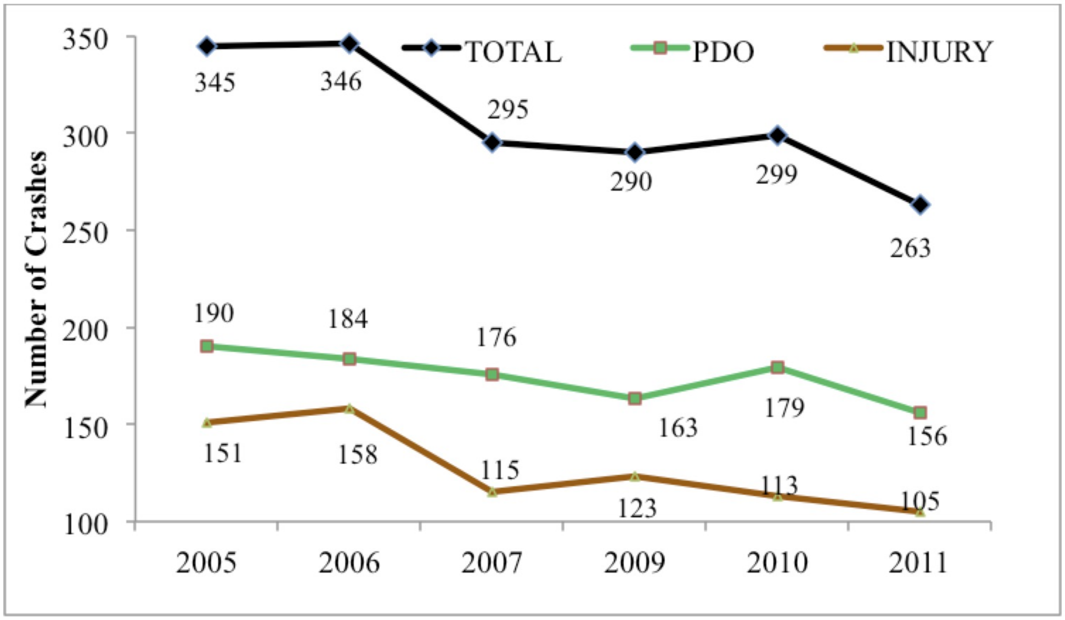

Figure 3.7. Crash severity

There is a slight increase in the fatalities mainly due to a spike in fatalities in 2010. 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 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 3.8 shows these changes in collision types during before and after periods. Single vehicle crashes are seen as the most significant type of collisions in both periods.

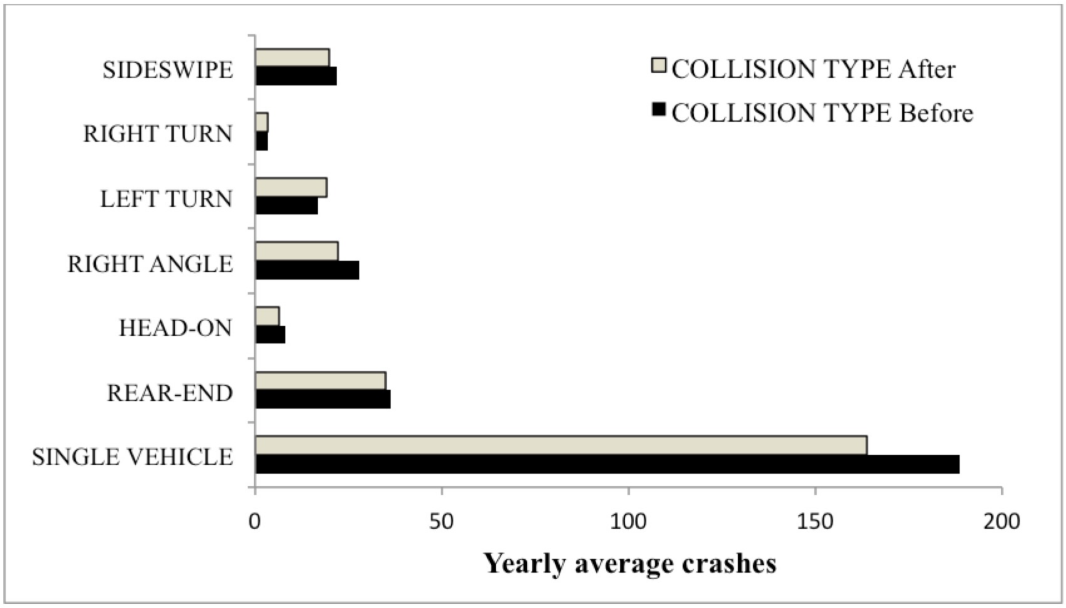

Figure 3.8. Types of collisions in before-after periods

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

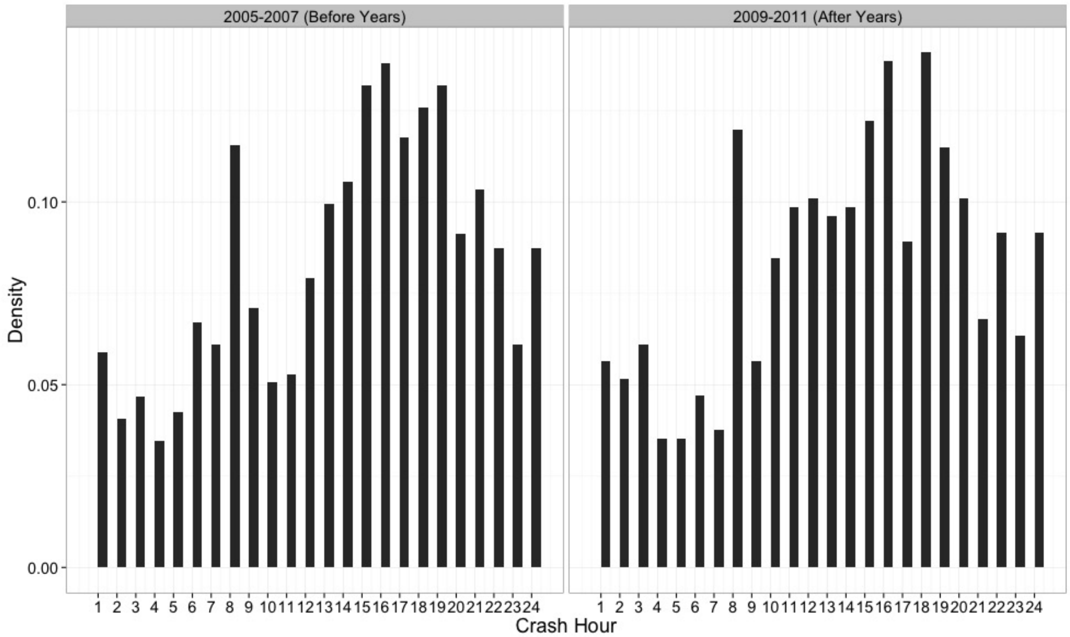

Figure 3.9. Density plot of crash hour in before-after periods

Table 3.3 lists the number of crashes under different lighting conditions. The majority of crashes happened in daylight. As shown in Table 3.3, daylight crashes decreased by 14% and night time crashes (with no street light) decreased by 12%, but crashes under proper lighting conditions seemed to increase. Roadway segments with proper lighting saw a 16% increase in the number of crashes after the implementation of edge lines.

Table 3.3. Crash frequencies under different lighting condition

Lighting Condition	**2005**	**2006**	**2007**	**2009**	**2010**	**2011**
Daylight	203	211	169	174	168	157
Dark with No Street Lights	114	117	103	93	113	88
Dark with Continuous Street Lights	7	6	6	9	4	9
Dark with Street Lights at Intersection Only	7	1	2	5	5	3

Figure 3.10 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 they are 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).

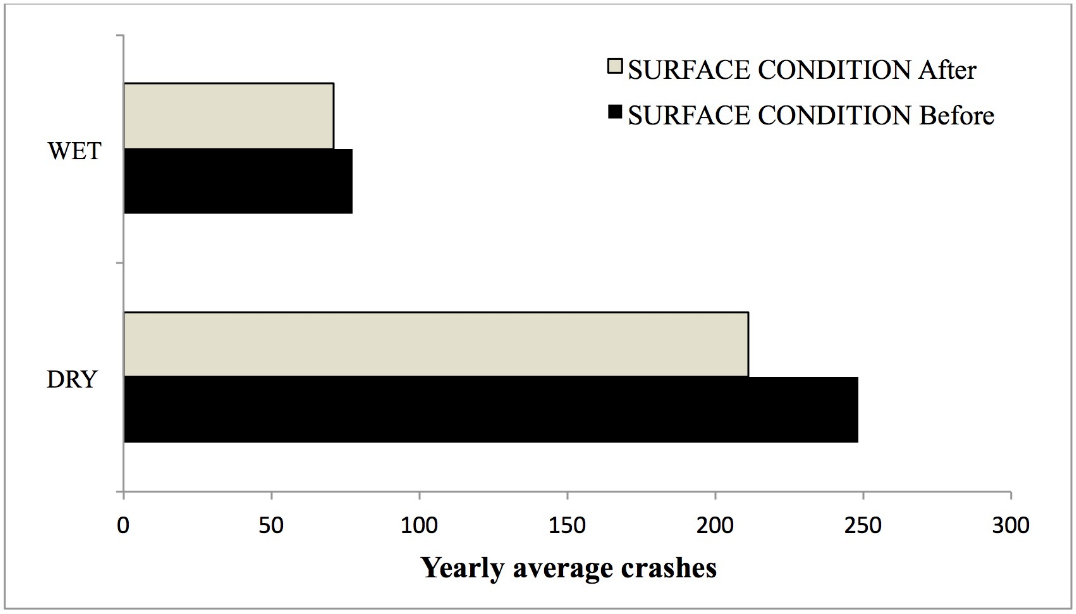

Figure 3.10. Surface condition in before-after years

3.5.3. Driver Characteristics

The human factor is considered 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 incorrect 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 broader 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. Driving tasks such as speed and headway selection, lane maintenance, and lane changing varies with different driver profiles (normal, aggressive, distracted, impaired, drowsy, reckless, cautious, etc.). About 52% of driving license holders of Louisiana 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 3.11. It is seen that female involvement in crashes does not change much after the installation of edge lines. In the crash database, about 5% records have no driver gender information, which explains why the sum of male and female crashes does not add up to the total number of crashes.

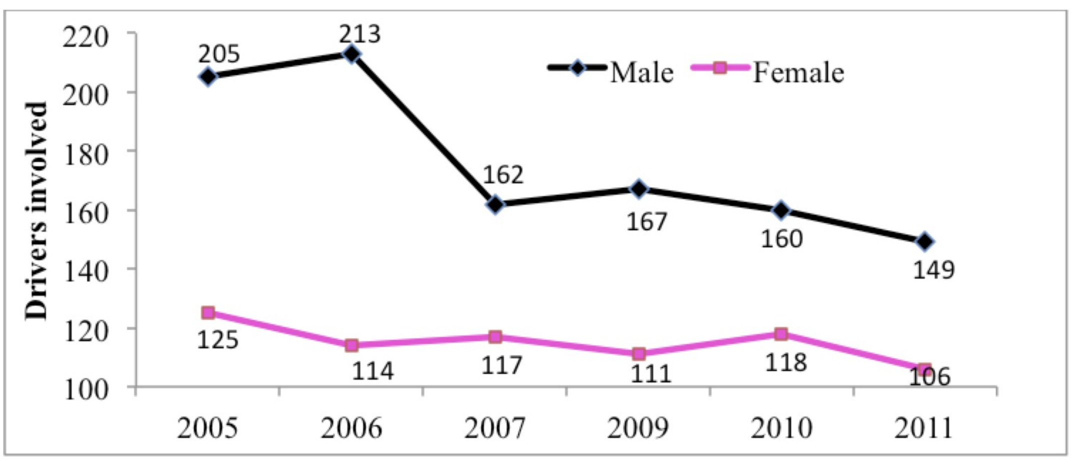

Figure 3.11. Male and female drivers in traffic crashes

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 the age of the drivers was plotted in Figure 3.12. 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. Crashes increased with age in the middle-aged group. On the other hand, there was an 8% increase in crashes in age group 55-64.

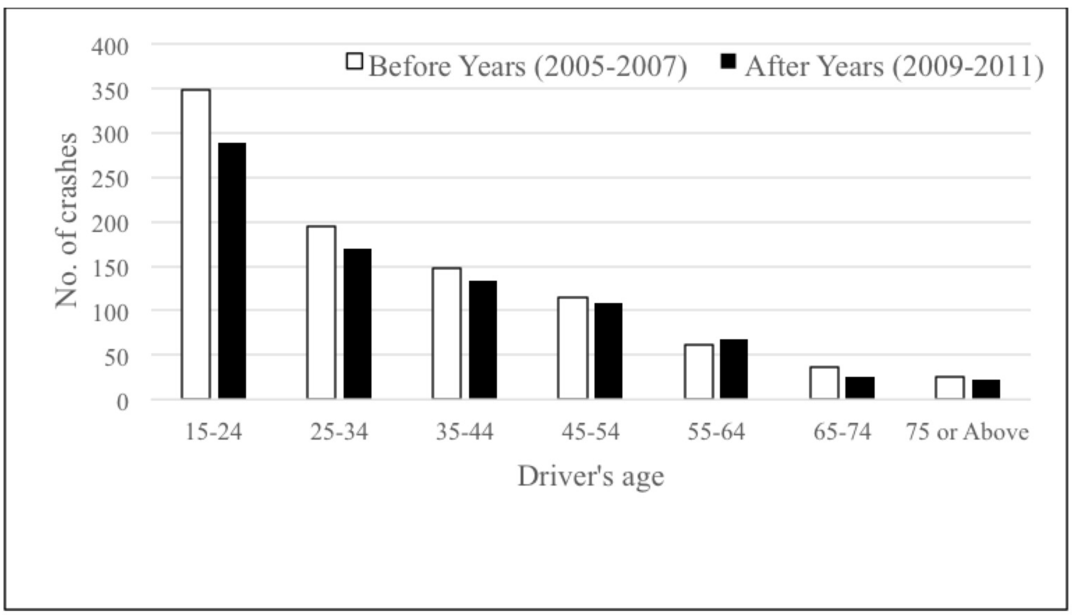

Figure 3.12. Driver age distribution

Figure 3.13 and Figure 3.14 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 researches. A large and expanding body of research has documented the myriad ways in which distraction can impact 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 maintain their proper guided way.

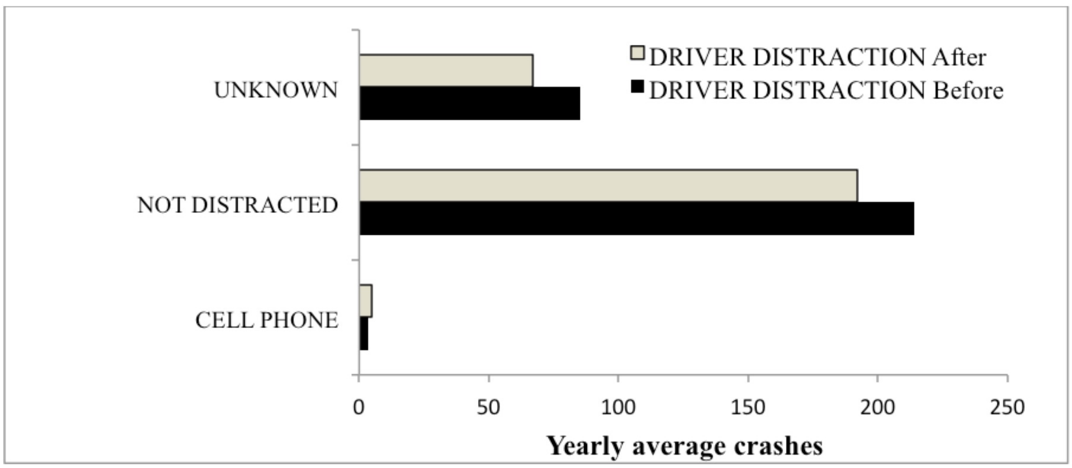

Figure 3.13. Driver distraction related crashes in before and after period

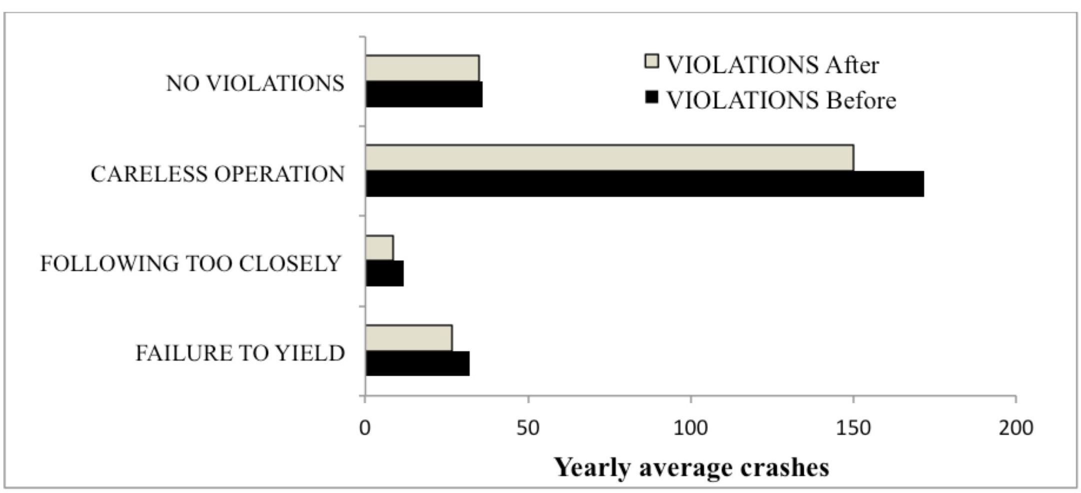

Figure 3.14. Driver violation induced crashes in before and after period

3.5.4. Vehicle Speed

Various categorical and numerical variables were considered for analysis in this study. 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, drivers age, posted speed, estimated speed, and crash hour. Estimated driving speed (drivers operating speed) and crash hour are considered to be two important numerical variables because of their significant impact on the safety outcome of edge line markings. EDA performed on the various variables altogether occasionally explores hidden knowledge structure inside the data. Figure 3.15 illustrates the distribution of operating speed by crash severity and crash hour for the before and after time periods.There is a close association 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, 25% of fatal crashes were seen to have occurred under lower speed at night. In the before years, there was no fatal crashe in lower speed at night. This information indicates involvement of other factors not associated with edge line installation. Around 40% of the fatal crashes were happened in the nighttime in the before years. This percentage reduced to 25% in the after years. For injury and PDO crashes, high speed driving has higher concentration of crash occurrences.

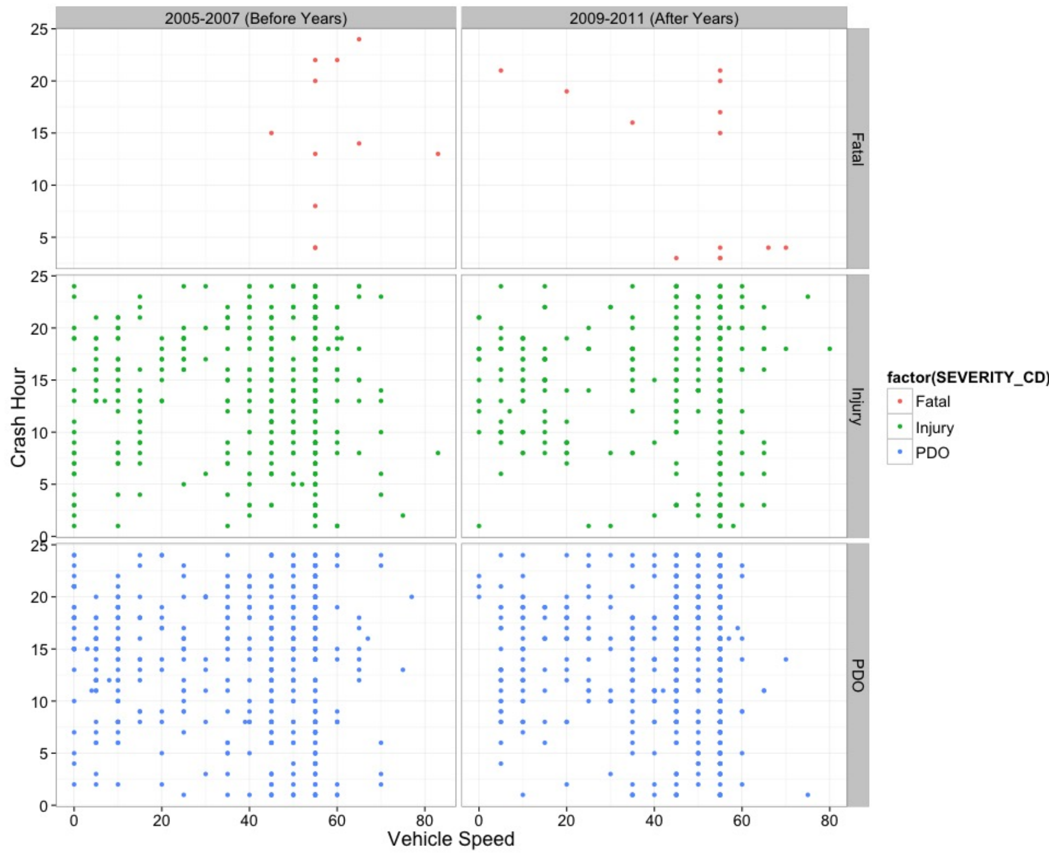

Figure 3.15. Crash hour vs. speed plot for different severities

Figure 3.16 shows the association 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.

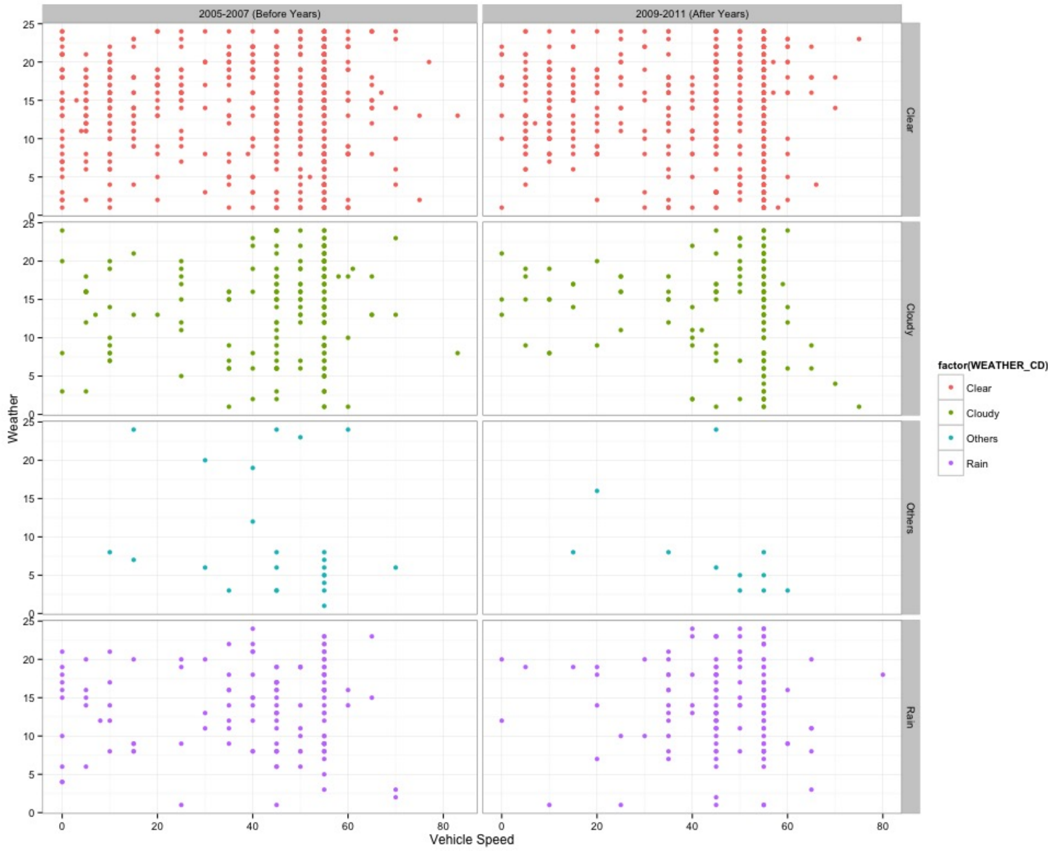

Figure 3.16. Crash hour vs. speed in different weather conditions

3.6. Discussion of Results

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

Table 3.4 gives annual crashes by pavement width on rural two- lane highways in

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

Table 3.4. Crash frequencies of roadways with different widths

Year	Width⩽20 ft.	20 ft.<Width<22 ft.	Width =22 ft.	Width>22 ft.	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%**

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

The cost for installing 6-in. edge lines varies depending on the cost of labor and materials. To develop the benefit-cost ratio for edge line implementation, three unit costs were used in the calculation. The benefits were computed by the crash reduction at three severity levels. According to the Louisiana data, the average cost was $4,376,304 for a fatal crash, $137,670 for an injury crash, and $3,292 for a PDO crash. Installing edge lines reduces crashes, and thus the benefits are estimated by crash costs as shown in Table 3.5 .

Table 3.5. Benefit-cost analysis

Cost	**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		
Benefit	**Paint (DOTD)**	**Paint (Contractor)**	**Thermoplastic (Contractor)**
Cost per lane mile	$450	$700	$2,800
Total cost	$98,676	$153,496	$613,984
Benefit-cost ratio	117.53	75.56	18.89

Because of the lack of SPF models for fatal and injury crashes, the observed reduction of crashes was used for benefit calculations. The estimated benefitcost ratio for edge line installation ranged from 18.89 to 117.53 on the basis of the labor and material costs shown in Table 3.5.

3.7. Conclusions

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

CHAPTER 4: INVESTIGATING SAFETY IMPACT OF RAISED PAVEMENT MARKERS ON FREEWAYS IN LOUISIANA

Abstract

Raised pavement markers (RPM) are intended as inexpensive safety devices on roadways. Intuitively convinced by its safety benefits, the DOTD has been using RPMs for many years on all freeways in Louisiana. Because of the not-so-positive CMF value after using RPMs published by the first HSM the state has to evaluate safety benefits of RPMs in a warm climate. This study aims to investigate the safety effect of the RPMs on freeway crashes with nine years of Louisiana traffic crash data. The safety effect of freeway striping was also evaluated since the condition rating on RPMs and stripings are made concurrently every year. The analysis results from the two methods indicate that RPMs have a significant effect in reducing crashes, particularly nighttime crashes at all AADT levels. For AADT under 20,000, the probability of a positive safety effect is given by the HSM as 0.26 with 1.13 CMF and a standard error of 0.2. For the same AADT, the probability of a positive safety effect is estimated by this study as 0.97 on rural freeways. The CMF developed for rural freeways by using improved prediction method is 0.96. Results from these methods indicate positive safety effect of using RPMs in rural freeways. The analysis results also indicate that RPMs do not have any safety benefits on urban freeways.

4.1. Introduction

A raised pavement marker (RPM) is intended as a safety device installed on roadways. These devices are usually made with plastic, ceramic, or occasionally metal, and come in a variety of shapes and colors. Some varieties include a lens or sheeting that enhances their visibility by reflecting automotive headlights.

Explicitly convinced by its safety benefits, DOTD has been using RPMs for many years on all freeways in the state. As with many highway devices, RPMs need to be replaced periodically to maintain their intended functionality, which requires significant resources. To select the most efficient crash countermeasure under the limited resources, the effects of all crash countermeasures need to be understood and qualitatively measured. Although the safety benefit of RPMs is intuitively felt by drivers in Louisiana, there are not many qualitative studies conducted showing its capability in crash reductions. The CMF value for using RPMs listed in the first edition of the HSM is greater than one for roadways with AADT less than 20,000. It means negative safety effect is visible after usage of RPMs. There is a need to substantiate the effect of RPMs in order to decide the continuation of using RPMs on freeways in Louisiana, which is precisely the objective of this study.

4.2. Literature Review

Due to its popularity, numerous studies were conducted on the evaluation of RPMs. But the majority of these researchers were concerned with RPM installation procedures, durability, retro reflectivity, costs, and optimum spacing. Relatively few studies have been conducted during the last 30 years on the safety effectiveness of RPMs.

Wright et al. evaluated the safety effectiveness of reflective raised pavement markers in 1982 (Wright et al., 1982). 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 a 22% reduction in nighttime crashes compared to daytime crashes at the same sites.

A before-after study was conducted by Kugle et al. in 1984 (Kugle et al., 1984). Two years of before-after crash data from 469 Texas sites (varying in length from 0.2 to 24.5 miles) were used for analysis. About 65% of study sites were on two-lane roads, the rest were mostly on four-lane roadways. Three different evaluation methods were used in this study. The results showed there was an increase in nighttime crashes by 15% to 30% after RPM installation. Mak et al. performed a study on the same dataset as Kugle et al. to re-examine the impact of RPMs on the nighttime crashes (Mak et al., 1987). In this study, the locations of the previous study were reinvestigated to specify the safety effect of RPMs 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% of sites showed a significant decrease in nighttime crashes, 10.3% of sites showed a significant increase in crashes, and the remaining 85.1% showed non-significant effects. Griffin analyzed the re-screened data from the Mak et al. study by employing a different statistical approach (Griffin, 1990). Using yoked comparison before-after methodology, the expected change in nighttime crashes following the installation of RPMs 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-after methods to assess the safety impact of RPMs on the nighttime crashes on both divided and undivided arterials in Michigan (Pendleton, 1996). Seventeen locations (length=56 miles) were considered as treatment sites, and 42 sites (length= 146 miles) were used as control sites with no RPMs. 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-after methodology.

The New York State Department of Transportation (DOT) performed a simple before-after safety investigation of RPMs in New York. In this study, the number of crashes prior to and after the placement of RPMs was compared without controlling for other factors (NY8, 1989). 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 used the same methodology as Griffin to assess the effects of raised pavement markers on nighttime crashes at 91 Interstate highway locations in Pennsylvania (Orth-Rodgers Associates, 1998). The results showed a significant crash increase of 18% in nighttime crashes, a 30 to 47% crash increase at nighttime under wet pavement conditions.

The above-discussed studies have conflicting conclusions on the impact of RPMs, which called for a comprehensive study by the National Cooperative Highway Research Program (NCHRP) in 2004 to evaluate the safety effects of raised pavement markers (Bahar, 2004). The data from two-lane and four-lane highways were collected from the six states for the analysis. The NCHRP study developed the CMF for rural four-lane freeways that is published in the first edition of HSM as shown in Table 4.1 (AAS, 2010).

Table 4.1. CMF for RPM in HSM for rural four-lane freeways (all severity)

Traffic Volume (AADT)	**Crash Modification Factor (CMF)**	**Standard Error**
$\leqslant 20,000$	1.13	0.2
20,001-60,000	0.94	0.2
>60,000	0.67	0.2

In summary, the previous studies on the safety effectiveness of RPMs 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 RPMs on roadway safety when AADT is less than or equal to 20,000. There are 40% of rural freeways in Louisiana have AADT less than or equal to 20,000. (97.2% of Louisiana rural freeways are four-lane highways). None of the rural freeway segments in Louisiana before year 2010 has AADT higher than 60,000. A study is thus needed tp explore the scopes and effectiveness of using RPMs in Louisiana freeways.

4.3. Initial Data Analysis

In Section 3B.12 of MUTCD, it is mentioned: retroreflective or internally illuminated raised pavement markers may be used as positioning guides with longitudinal line markings without necessarily conveying information to the road user about passing or lane-restrictions. In such applications, markers may be positioned in line with or immediately adjacent to a single line marking, or positioned between the two lines of a double center line or double lane line marking. The options are:

- Where it is desired to alert the road user to changes in the travel path, such as on sharp curves or on transitions that reduce the number of lanes or that shift traffic laterally, the spacing may be reduced.

- On freeways and expressways, the spacing may be increased for relatively straight and level roadway segments where engineering judgment indicates that such spacing will provide adequate delineation under wet night conditions.

The commonly used RPMs by DOTD are shown in Figure 4.1. DOTD use various brands of RPMs like Stimsonite Model 948AW (two way white), Stimsonite Model 948 ERW (white/red), Stimsonite Model 948 AY (two way yellow), Stimsonite Model 948 BW (one way white), Stimsonite Model 911BY (one way yellow), Rayolite 20021W (one way white), Apex Model 921 AR (white/red), and Stimsonite Model C80 ERW (white/red). The quality of RPMs along with pavement stripings (center and edge lines) on Louisiana freeways was inspected annually by a designated engineer who gave subjective ratings. Three categories of rating (good, fair and poor) are used to describe the condition of RPMs and stripings. The segments in poor condition will be scheduled for either RPM replacement or re-striping. The nine years (2002-2010) ratings of RPMs and stripings 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 for striping 3.28 years. During the nine years, a segment would experiences several cycles (from good to poor) of ratings for RPMs or stripings.

Figure 4.1. Commonly used RPMs

The ratings of RPMs and stripings were 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, and AADT remain the same. The nine year crashes were populated to each segment based on their longitudinal and latitudinal coordinates.

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 freeway design and operation, the analysis is conducted for rural and urban sections 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 RPMs and the second for stripings (G as good, F as fair and P as poor). The summary of ratings is listed in Table 4.2.

Table 4.2. Number of segments with different ratings

Number of Control Sections in Each Rating Group									
Freeway Location	**Good Good (GG)**	**Good Fair (GF)**	**Good Poor (GP)**	**Fair Good (FG)**	**Fair Fair (FF)**	**Fair Poor (FP)**	**Poor Good (PG)**	**Poor Fair (PF)**	**Poor Poor (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

Excluding the mixed ratings from RPMs and stripings, the first focus of the analysis was only on the cases with both ratings in the same category. Figure 4.2 compares of the crash rate for the rural freeway segment, where the overall average crash rate for both RPMs and stripings with quality rating k, $\bar{R}_k$ is computed as:

$$\bar{r}_{ki} = \frac{\sum_j r_{kij}}{M_k} \tag{4.1}$$

$$\bar{R}_k = \frac{\sum_i \bar{r}_{ki}}{N} \tag{4.2}$$

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

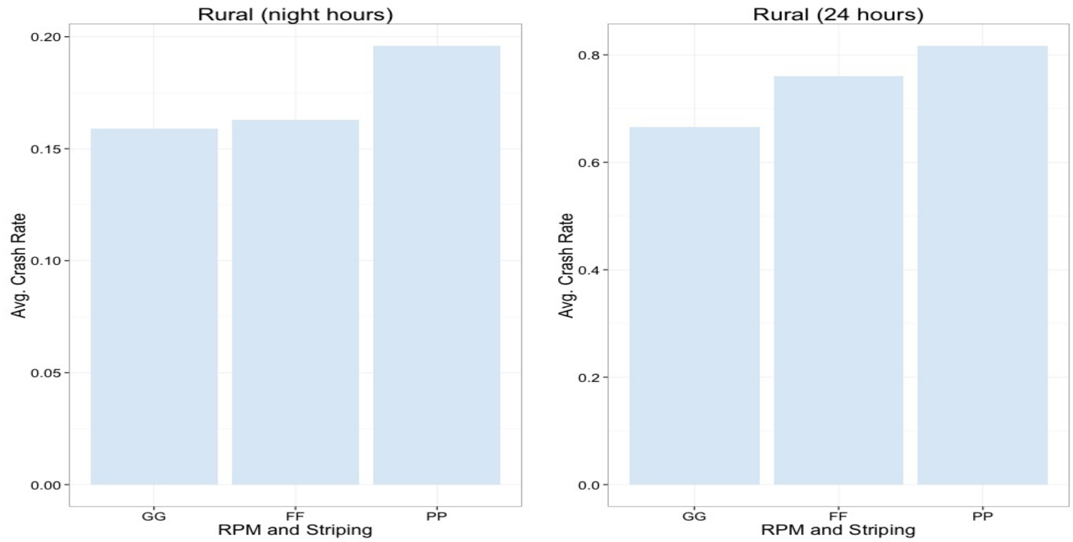

Figure 4.2. Average crash rate by different ratings on rural freeway

It is encouraging to see that the quality of RPMs and stripings does make a difference in the crash rate. As the combined ratings go from good to poor, the overall average crash rate increases. Since RPMs are particularly important at night for outlining traveled lanes, the nighttime crash rate is also computed with the 24-hour AADT, which shows the same trend. The increasing crash rate from a rating of good to poor is 22% for 24-hour crash rate calculation, and 23% for nighttime crash rate estimation. However, as shown in Figure 4.3, the overall average crash rates do not reveal any positive effect of RPMs and stripings on the urban freeways, which is similar to the CMF listed in the first edition of HSM.

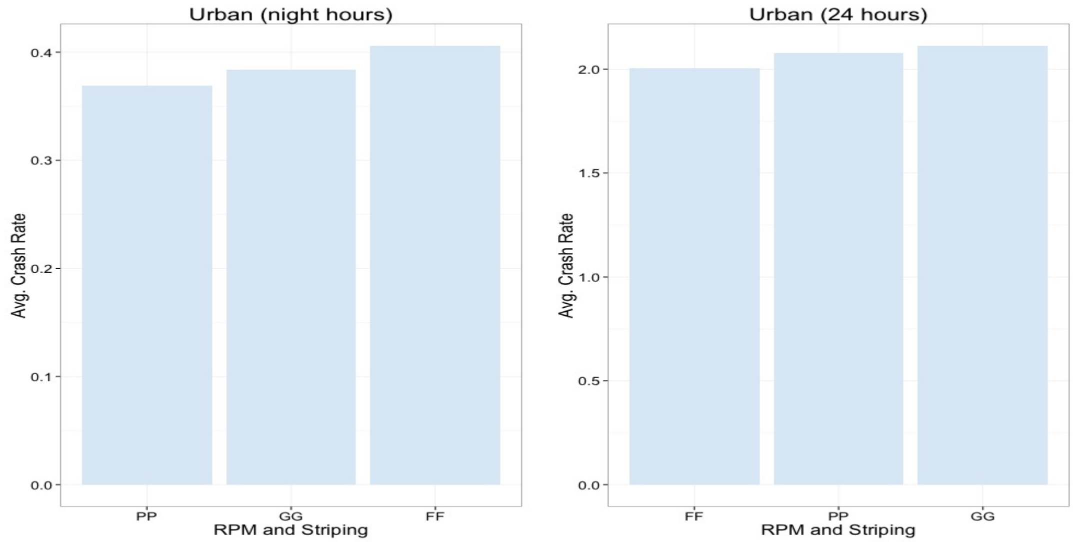

Figure 4.3. Average crash rates by different ratings on urban freeway

It is a challenge to estimate the safety effect of RPMs and stripings separately since both have somewhat similar functionalities. Figure 4.4 illustrates how overall average crash rates on rural freeways vary by either RPM or striping ratings at both 24 and night hours.

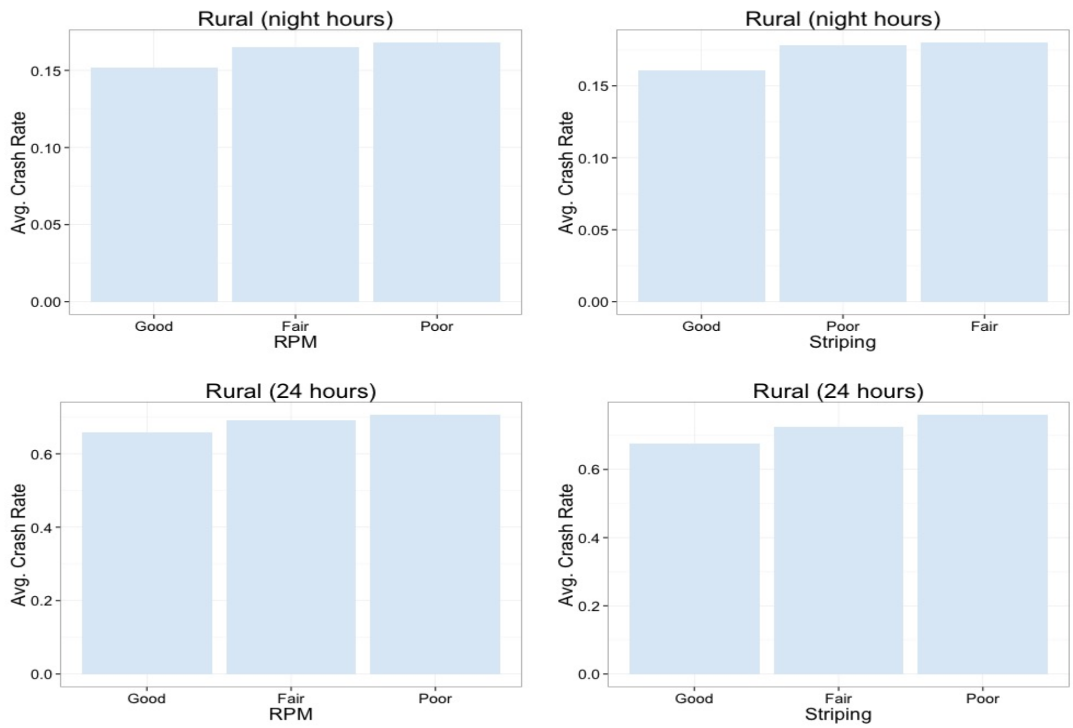

Figure 4.4. Average crash rates by single rating (RPM or striping)

The positive safety effect is still evident even with only one single rating as shown in Figure 4.4 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 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 a rating of good and poor for a single feature is not as big as the difference in the combined ratings between GG and PP. But nevertheless, the initial data analysis does demonstrate the safety effect of RPMs and stripings independently.

4.4. Methodology

The research hyposthesis is: using RPMs will improve traffic safety. In other words, there's a significant decrease of traffic crashes in the after years for RPM installation. Two different statistical methods were used to determine the safety effectiveness of RPMs: 1) Repeated measure test, 2) Before-after improved prediction method.

4.4.1. Repeated Measure Test

The initial analysis results show the difference in crash rate between good and poor ratings for RPMs and stripings. Whether or not these differences are significant in the statistical terms were 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. As this statistical analysis is conducted on the same control sections with a new treatment. One-way repeated measure test would be good test to examine the research hypothesis of positive safety effects of RPMs. The difference in crash rates under good and poor ratings is examined by the t-test at three AADT levels. The results of the repeated measure testing are listed in Table 4.3.

Table 4.3. Results of repeated measure

Roadway Type	Hour of the Day	t-value	df	Sig. (2-tailed)	Mean Diff.	Std. Error Diff.	95% CI (Lower)	95% CI (Upper)
AADT <20,000								
Rural 4-lane	Night	-2.603	309	0.010	-0.063	0.024	-0.110	-0.015
Rural 4-lane	24-hrs	-2.591	309	0.010	-0.212	0.082	-0.373	-0.051
20,000<AADT<60,000								
Rural 4-lane	Night	-2.285	492	0.023	-0.047	0.020	-0.087	-0.007
Rural 4-lane	24-hrs	-2.840	492	0.005	-0.168	0.059	-0.284	-0.052
AADT >60,000								
Rural 4-lane	Night	-2.800	889	0.005	-0.045	0.016	-0.077	-0.013
Rural 4-lane	24-hrs	-3.504	889	0.000	-0.186	0.053	-0.289	-0.082
Note: df= Degrees of Freedom, Sig.=Significance, Std.= Standard, Diff.= Difference, CI= Confidence Interval								

The statistics testing results show the safety effect of RPMs and stripings slightly varies by AADT. The crash rate difference between two ratings is, indeed, statistically significant for RPM installation for any AADT level. The negative lower and upper bound of the estimated mean difference at a 95% confidence level ascertains the positive effects of RPMs and stripings for the rural freeways with different AADT range. For the rural freeway segments with AADT less than 20,000, the crash rate difference between two combined ratings of RPM and stripings is only statistically significant at 24-hr consideration (at a 90% confidence level). Absence of any positive upper or lower bound indicates indicates the positive safety effectiveness of using RPMs and stripings in rural freeways.

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, it will not be sufficient to simply compare their values. However, the effect of RPMs expressed by the CMF and crash rate difference can be illustrated by the probability calculation. For AADT under 20,000, probability of a 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 a 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 4.5.

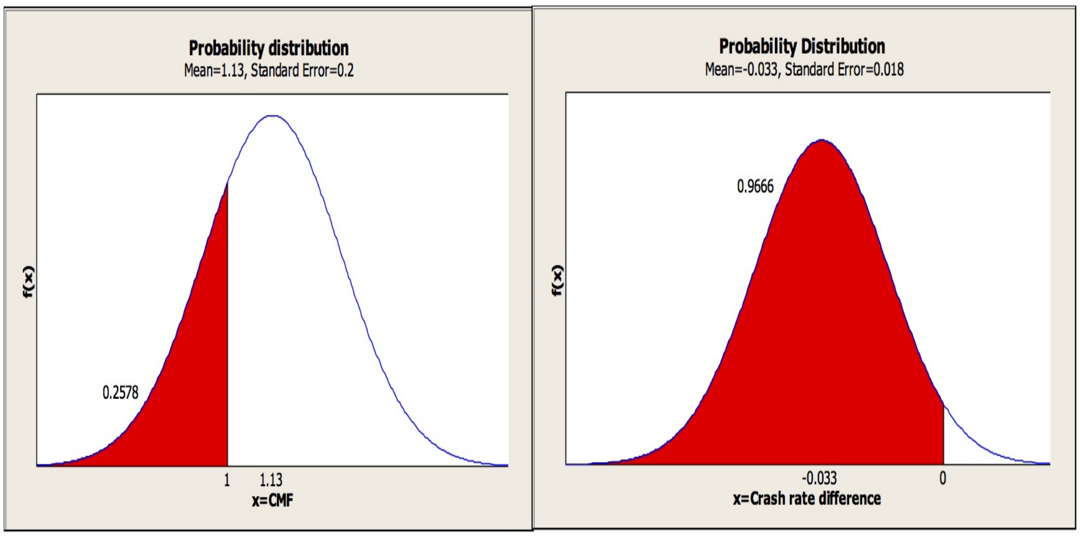

Figure 4.5. Probability of positive safety effect of RPM

For AADT between 20,000 and 60,000, the probability of a positive RPM effect is 1 from this study and is .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.

4.4.2. Improved Prediction Method

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. We know that the EB method predicts the expected safety 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, I need to use improved prediction method to estimate a CMF for the RPM installed sites [15]. The details of the safety estimation are summarized as follows:

Step One: Estimating the safety if the RPMs and stripings are not installed during the after period, $\hat{\pi}$, and the safety with the RPM (with striping) installed project , $\hat{\lambda}$.

$$\hat{\lambda} = N \tag{4.3}$$

$$\hat{\pi} = \hat{r}_{tf} K \tag{4.4}$$

Where,

$\hat{\lambda}$ = Estimated expected number of crashes in the after time period with RPMs and stripings

N = Observed annual crashes after RPM (with striping) project

$\hat{\pi}$= Estimated expected number of crashes in the after period without the RPMs and stripings

K = Observed crashes before the RPM (with striping) project

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

Step Two: Estimating the variance of, $\hat{\lambda}$, and $\hat{\pi}$.

$$V\hat{A}R(\hat{\lambda}) = N \tag{4.5}$$

$$V\hat{A}R(\hat{r}_{tf}) = (\hat{r}_{tf})^2 v^2 (\hat{A}_{avg} + \hat{B}_{avg}) \tag{4.6}$$

$$V\hat{A}R(\hat{\pi}) = (r_d)^2[(\hat{r}_{tf})^2 K + K^2 var(\hat{r}_{tf})] \tag{4.7}$$

Where,

$V\hat{A}R(\hat{\lambda})$ = Estimated variance of $\hat{\lambda}$

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

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

v = The percent coefficient of variance for AADT estimates

$= 1 + \dfrac{7.7}{t} + \dfrac{1650}{AADT^{0.82}}$ [where, t= number of count-days]

$V\hat{A}R(\hat{\pi})$= Estimated variance of $\hat{\pi}$

Step Three: Estimating the crash difference, $\hat{\delta}$, and safety effectiveness $\hat{\theta}$.

$$\hat{\delta} = \hat{\pi} - \hat{\lambda} \tag{4.8}$$

$$\hat{\theta} = \frac{\frac{\hat{\lambda}}{\hat{\pi}}}{1 + \frac{V\hat{A}R(\hat{\pi})}{(\hat{\pi})^2}} \tag{4.9}$$

Where,

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

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

Step Four: Estimating the standard deviation of the crash difference, $\hat{\delta}$, and safety effectiveness $\hat{\theta}$.

$$\hat{\sigma}(\hat{\delta}) = \sqrt{V\hat{A}R(\hat{\lambda}) + V\hat{A}R(\hat{\pi})} \tag{4.10}$$

$$\hat{\sigma}(\hat{\theta}) = \hat{\theta}\frac{\sqrt{\frac{V\hat{A}R(\hat{\lambda})}{(\hat{\lambda})^2} + \frac{V\hat{A}R(\hat{\pi})}{(\hat{\pi})^2}}}{1 + \frac{V\hat{A}R(\hat{\pi})}{(\hat{\pi})^2}} \tag{4.11}$$

Where,

$\hat{\sigma}(\hat{\delta})$= Standard deviation of $\hat{\delta}$

$\hat{\sigma}(\hat{\theta})$= Standard deviation of $\hat{\theta}$

The results of the improved prediction method are listed in Table 4.4. The results show a 4% reduction of rural roadway crashes due to the installation of RPMs with stripings.

Table 4.4. Results from improved prediction method

DOTD District	No. of Control Section	Safety Effectiveness, $\hat{\theta}$	$\hat{\sigma}(\hat{\theta})$	$\hat{\theta} + 3 \times \hat{\sigma}(\hat{\theta})$	$\hat{\theta} - 3 \times \hat{\sigma}(\hat{\theta})$
All	290	0.96	0.018	1.014	0.916

4.5. Benefit-cost Analysis

This study also performed benefit-cost analysis of the RPM installation. The benefit-cost ratio ranges from 1:6 to 1:25 based on different clustered groups and market price variability with labor cost.

4.6. Conclusions

Among the two analyses that all show the positive impact of RPMs on rural freeway safety in Louisiana, it is believed that the results from the statistical test offer the most reliable information. The CMF value for using RPM in rural roadways shows some positive effect.

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

Although the ratings on RPMs and stripings are subjective, it is believed that the errors caused by the subjective evaluation from one single designated engineer 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 RPMs under fair conditions were not included in the analysis.

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

CHAPTER 5: COMMERCIALIZATION CHAPTER

5.1. Motivation

A study of the National Highway Traffic Safety Administration (NHTSA) shows that traffic crashes have huge impact on the economic development and society. Highway crashes in the U.S. result in $871 billion in economic and societal loss in 2010. The economic loss is equivalent to $900 per person and $594 billion suffering cost from fatality and decreased quality of life due to injuries (Blincoe et al., 2015).

Table 5.1 shows the average cost of crash by severity in Louisiana. The state crash database maintains three severity categories (severe, moderate, complaint) instead of five severity categories usually used. Therefore, the cost for Louisiana traffic injuries is the average of two of the injury categories used in the NHTSA study. Adjustments were done by using cost performance indicator (CPI) to obtain recent year traffic cost values. Based on these values, the total cost of the 2013 crashes for Louisiana was $5.6 billion and total cost due to decreased quality of life was $5.69 billion (Schneider, 2013). Safety engineers aim to reduce traffic crashes by introducing effective crash countermeasures. Under financial constraint, the inexpensive crash countermeasures are particularly considered as the best alternatives. Using DMADV to determine the safety effectiveness of inexpensive countermeasures in Louisiana has not been done yet. Thus, selection of inexpensive countermeasures and developing a commercialization framework would be beneficial for improving safety.

Table 5.1. Cost of crashes by severity

Severity Type	Average cost per person (in USD)	Including loss of quality of life (in USD)
Fatal	1,319,231	4,544,623
Injury	72,091	139,103
Property Damage Only (PDO)	3,418	3,418

5.2. Introduction

This study used the DMADV tool to select the most appropriate and inexpensive countermeasures for Louisiana to reduce traffic crashes and crash severities. As outlined in Chapter one, the following steps were taken in selecting crash countermeasures: (1) enlisting all feasible inexpensive countermeasures for Louisiana, (2) identifying all practical combinations of countermeasures, (3) identifying the advantages and disadvantages, and (4) measuring crash effectiveness. After conducting an extensive literature review and developing a prioritization matrix, three inexpensive countermeasures were selected for final evaluation. A complete benefit-cost analysis was performed on the selected countermeasures to complete the design verification stage. The basic steps for developing the commercialization tool are shown in Figure 5.1. A detailed breakdown of the steps is illustrated in Figure 5.2.

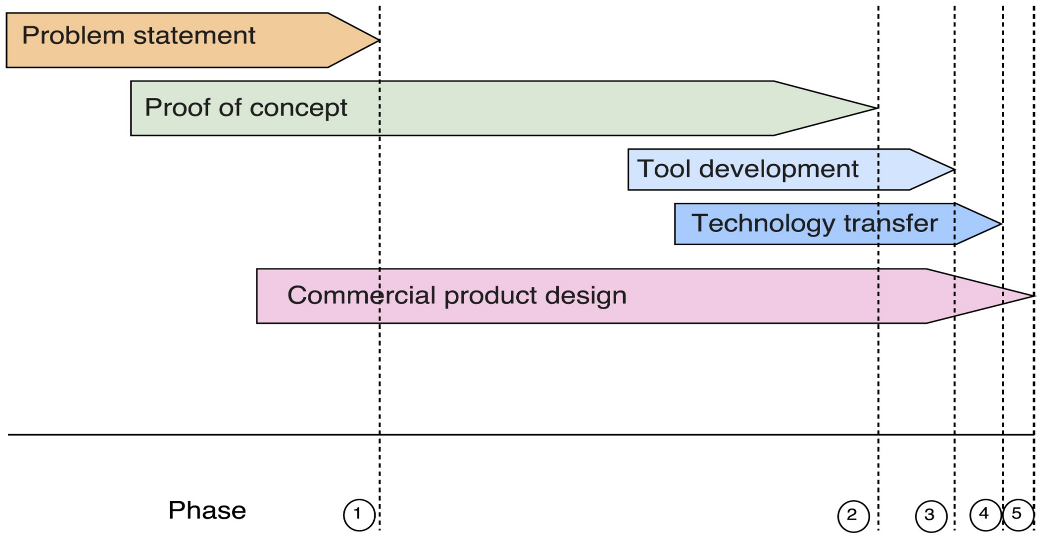

Figure 5.1. Steps for commercialization product

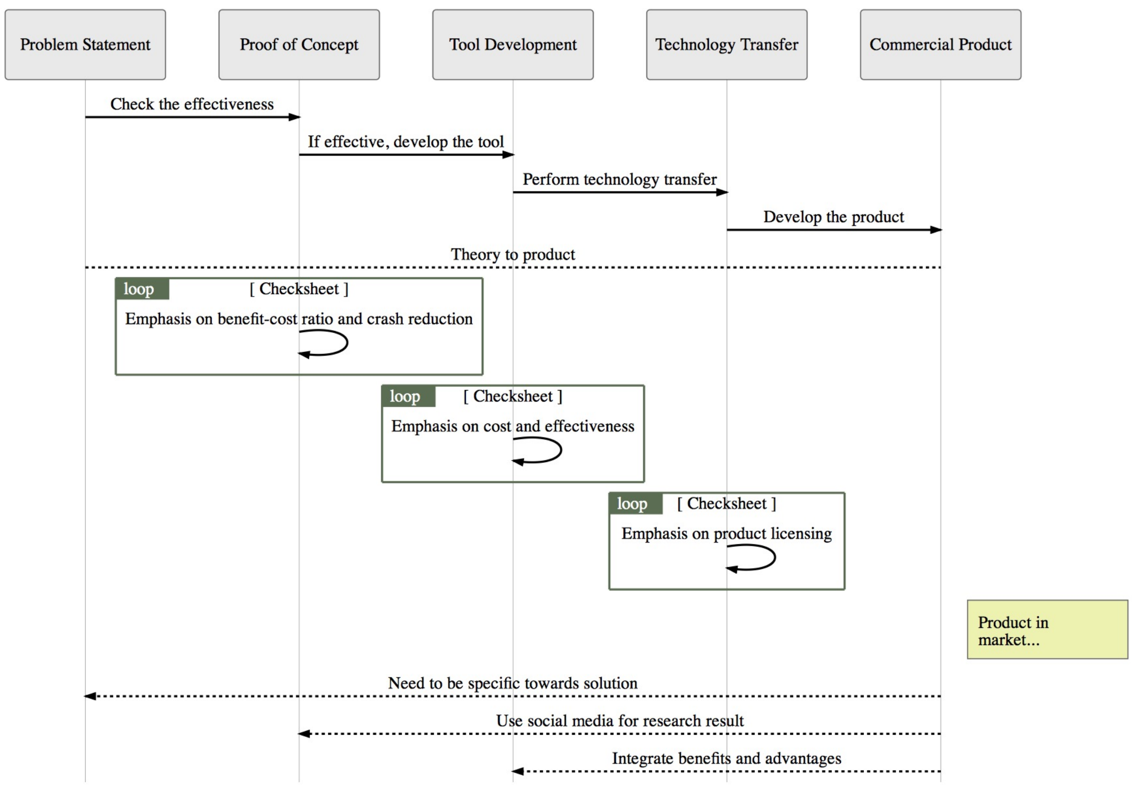

Figure 5.2. Breakdown of the steps

5.3. Problem statement

This dissertation aims to contribute to the reduction of traffic crashes and crash severities. Identifying the most appropriate and effective countermeasures helps enhancing traffic safety. After conducting the research, we found that systems approach is beneficial for road safety improvement. This study developed a systems methodology for the identification of appropriate inexpensive countermeasures that can be applied for any disaggregate level of federal or local government. Moreover, the tool can be used by private partnership companies for countermeasure effectiveness measurements and inexpensive product development. National and local government agencies have primary responsibility for traffic regulations, safety laws, infrastructure development, and site maintenance. Because these agencies are facing tighter budgets in the recent years, they have to make hard decisions on the selection of projects. An alternative approach is to make inexpensive safety tools to drastically improve safety. Sometimes, the decisions can be very comprehensive involving many stakeholders. In most cases, a ready-made alternative tool is effective to make all stakeholders understand the effectiveness of a design. Thus, this dissertation seeks to bridge the gap between commercial product design and successful research implementation.

5.4. Proof of concept

By using DMADV, this research successfully determines Louisiana-specific inexpensive crash countermeasures. The developed CMFs for these countermeasures show that implementation of these countermeasures contribute significantly in roadway traffic crash and severity reduction. Again under financial constraints, it is also important to know the cost effectiveness as well as customer feedback to these countermeasures. The validation of the selected countermeasures was done by using two methods: 1) Benefit-cost analysis, and 2) customer sentiment analysis by Twitter mining.

5.4.1. Benefit-cost analysis

In benefit-cost analysis, the economic effectiveness of crash countermeasures is determined. This means that it answers the question of whether the benefits of a countermeasure exceed the costs. An overview of costs and benefits can serve as a basis for prioritizing any particular countermeasure or package of countermeasures (combinations of measures). Moreover, benefit-cost analysis is useful because it summarizes a great deal of information in a more reliable framework. It helps the decision makers deriving the best policies or designing strategies. Table 5.2 lists the maximum and minimum benefit-cost ratios for all of these three crash countermeasures as described in details in Chapters 2, 3, and 4. The results indicate that using these countermeasures is extremely cost-effective.

Table 5.2. Benefit-cost ratios

Countermeasures	Minimum Benefit-cost ratio	Maximum Benefit-cost ratio
Conversion of four-lane undivided roadways to five-lane roadways with center lane TWLTL	1:166	1:199
Edge line on rural roadways	1:19	1:117
Raised pavement markers on rural freeways	1:6	1:25

5.4.2. Twitter Mining

Twitter is a relatively new social media tool for microblogging. The user posts, known as tweets, do not exceed 140 characters without any privacy conditions. It not only disseminates information but also reflects opinions. Twitter generates a huge amount of textual content daily. One can study textual content by means of text mining, natural language processing, information retrieval, and other data scientific methods. Figure 5.3

illustrates the flowchart of Twitter mining used in this study.

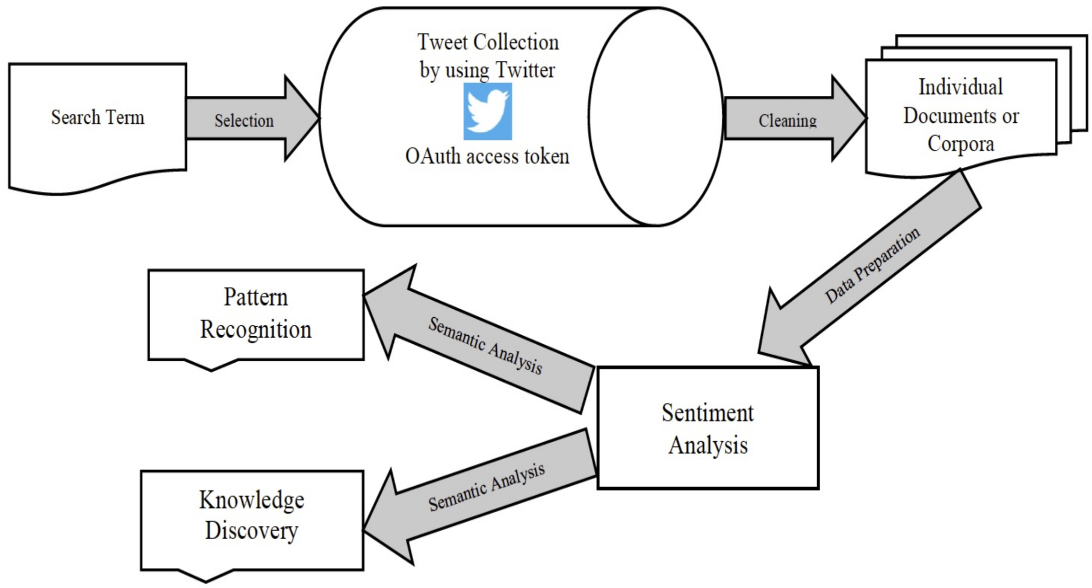

Figure 5.3. Twitter mining

Twitter currently implements two forms of authentication in the new model, both still leveraging open standard for authorization (OAuth). These two forms are: 1) Application-user authentication that is the most common form of resource authentication in Twitter's OAuth 1.0A implementation to date, and 2) Application-only which is a form of authentication where user application makes API requests on its own behalf, without a user context. It is important to note that the one-time tweet extraction limit from a Twitter handle is 3,200. A tidy dataset was prepared on the basis of the tweets with search terms (three countermeasures) having geo-location information.

Public sentiments are central to almost all human activities and are key influencers of our behaviors. Most human beliefs and perceptions depend on how others see and evaluate the world. It is important to note that the sentiment lexicons have domain-specific sentiment values; therefore sentiment classification performance of a given text may vary according to the calculation process of the sentiment for that text. This study used the senti-lexicon developed by Hu and Liu in 2004. The senti-lexicon was modified by including transportation safety related terms. A function named sentiscore, introduced by Breen, was used to produce the score count for each tweet (Das et al., 2015). This function was also partially changed to make it more traffic safety specific. The code of the function is added in Appendix A. This function mined each of the generated tweet by using the positive and negative word lexicons and produced a positive, negative or zero score. Figure 5.4 illustrates the sentiment score for the three countermeasures. The scores for these three countermeasures show more inclination towards the positive score.

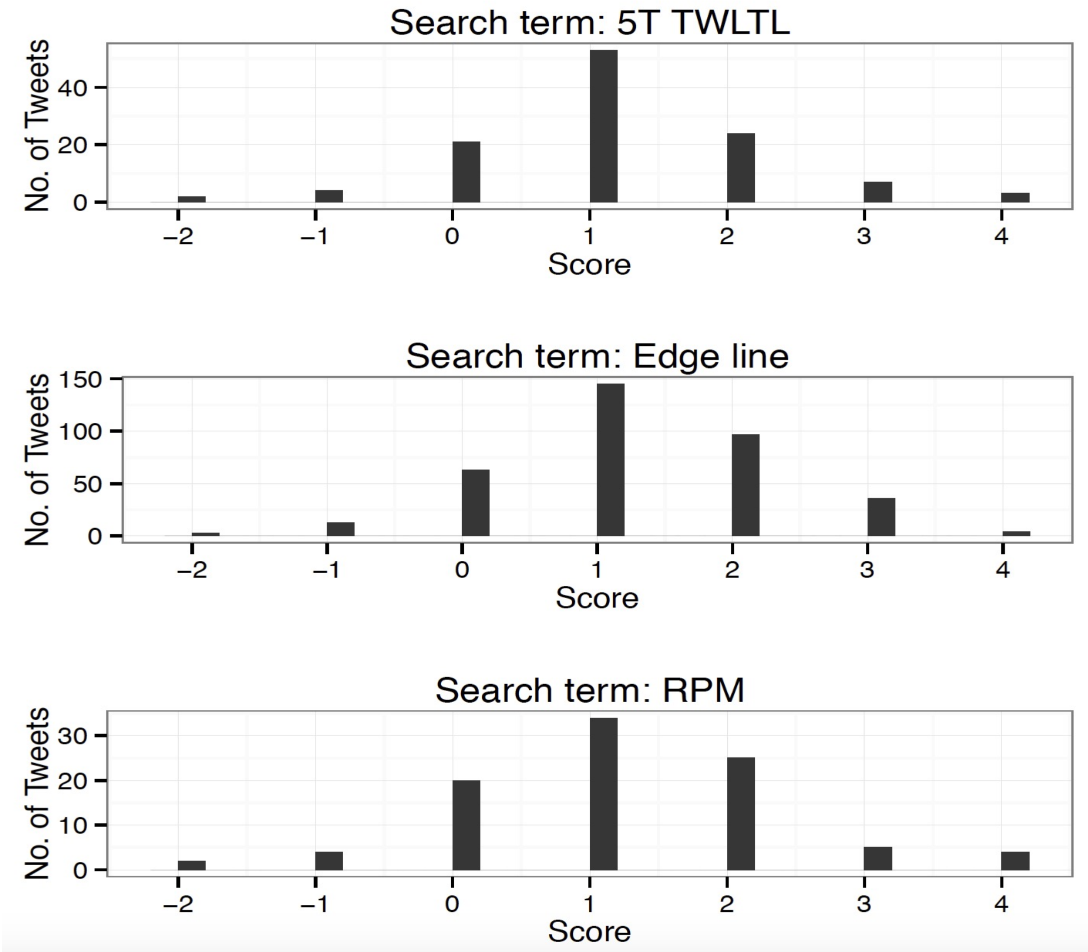

Figure 5.4. Sentiment score

5.5. Tool development

The commercial tool development phase requires adept understanding of research and business product development. It is very important to understand the customers and the federal policies. In this study, the commercialization process consists of five stages: defining commercialization and innovation through DMADV approach; reviewing existing models on federal research commercialization; establishing a safety effectiveness framework for countermeasure selection; conducting benefit-cost analysis; and developing disaggregate modeling frameworks. An appropriate business framework for federal level projects must evolve to support the different technical and economic stages of the implementation while also protecting the tax money of the roadway users. Making the stakeholders understand the need of a countermeasure or design alternative is usually very difficult as transportion engineering involves a very complex systems environment. Commercialization in any sector indicates the sequential decision process of coordinating and optimizing all of the engineering, economic, and strategic decisions required by the successful introduction of a new tool or solution in the existing environment. Additional actions like financing in process improvement, passing proper legislation, and creating proper institutional culture facilitate commercialization (Audretsch et al., 2011). A successful commercialization model serves as an excellent process roadmap that promotes best practices required to mitigate the obstacles along the path to market. So, it is very important to let customers know about the importance and advantages of the designed products. As all of the developed countermeasures have positive safety effect, it is possible to make the stakeholders favorable for adaptation. The effectiveness information can be circulated by social media, MPO public hearings, and university lectures and workshops.

The commercialization model concept for this project consisted of several phases that were consistent throughout the whole process. Each phase had specific characteristics and some phases required sub-phases to accomplish the task. Commercial transfer of technology from a federally conducted research to a commercial organization can improve technologies by undertaking the technical, economic, and manufacturing research. In this study, the producer is the laboratory or agency, and the user is both the road users and industry. For this case, the width of the edge line, spacings between the lanes, and the materials used for RPMs can be explored more through research for cost saving.

Another critical step in the study was to develop a definition of accurate technology transfer. Technology transfer and commercialization can occur along three different pathways. The direct pathway results in the exchange of products or processes, or collaborative research for developing technologies, between laboratories and other parties. The indirect pathway results in dissemination of knowledge through such mechanisms as publications, conferences, and teaching. The network pathway creates networks that may facilitate transfer through one of the other pathways and can accelerate movement along the trajectory of technology transfer to commercialization (Wessner, 1999). In this study, the direct pathway was used.

5.6. Technology Transfer

As the current dissertation is the product of federal money, one need to follow major issues while considering effective technology transfer: conceptions of theory and practical use, knowledge distribution, options of the stakeholders, data management, factors affecting transfer, and modes of transfer. In particular, a neatly defined model of technology transfer can be used as a structure for improved efficiency. There are many popular technology transfer models: the knowledge utilization model, the contextual collaboration model, the material transfer model, the appropriability model, the design transfer model, and the capacity transfer model. The knowledge utilization model is perfect in this particular situation as the research is conducted at a research-oriented university. This model emphasizes strategies that effectively deliver knowledge to the recipients. Issues related with knowledge transfer model are described below:

5.6.1. Data Management

The data management covered the collected data for the research at the University of Louisiana at Lafayette. All of the compiled information was non-classified and already in the public record that did not anticipate any confidentiality concerns. The data collected during this study were archived on the computer servers in the civil engineering department lab. The aim and purpose of this sub-phase was to detail and guarantee the preservation of the data collected during this study, as well as any results derived from the associated research.

5.6.2. Policies

There were no requirements stipulated by the funding or partner organizations regarding this data. Comprehensive institutional and research group guidelines specified by the University of Louisiana at Lafayette were applied regarding the collection of this data. There were no additional requirements associated with the data being submitted.

5.6.3. Standards and Management

The data was collected by using open source software and was analyzed by using open source statistical software. The plots and other calculations were performed by using open source software tool. In Appendix, the codes used for the figures are included. Research data was backed up on a daily basis. The long-term strategy for the maintenance, and archiving of the data were implemented when the data and associated research were complete and ready for public distribution.

5.6.4. Societal Mission

The project offered broad impacts that advanced the core societal mission of enhancement of educational offerings at the University of Louisiana at Lafayette and provided valuable interdisciplinary training opportunities related to transportation engineering and systems engineering core.

5.6.5. Education and Training

While conducting this study the research team worked closely with the Civil Engineering department for technology transfer and utilized the broader aspect of knowledge discovery in transportation research to resolve the safety problem. The department organized classroom lectures that gave the participants a hands on experience of CMF development. The materials for the lecture and workshop were designed to educate the public about traffic safety, systems engineering, and policy conceptualization. It targeted to assist communities to envision their future by establishing a collaborative export with its citizens through workshops and classroom lectures.

5.7. Commercial product design

This research implemented a unique DMADV methodology to design inexpensive countermeasures with positive safety impacts. The research product included the DMADV guidance associated with appropriate countermeasures with CMF values. The current method identified three inexpensive countermeasures which were best fit for Louisiana. The methodology can be considered as a complete set of tools which can be used as a research product and can be transfered in any aggregate or disaggregate level. As the developed product or commercial tool will require localized knowledge extraction, the used toolsets can be used in different locations with the input of adequate research synthesis. The knowledge extraction from the research synthesis would guide the selection of the suitable countermeasures. The verification and technology transfer guideline will be helpful for any research agency or private companies to make the federal research product commercially successful.

The commercial product design passed through the following steps:

- Utilizing DMADV tool to select most appropriate aggregate or disaggregate level inexpensive countermeasures
- Developing methodology for research synthesis and prioritization matrix
- Following the guidelines of technology transfer
- Making strategies to use social media and university resouces for the publicity of research results

5.8. Conclusions

The dissertation offers unique contributions to engineering research. The research provides new engineering research tools to make roadways safer for all road users. The research contributes in utilizing a Six Sigma DMADV methodology to increase traffic safety by evaluating three inexpensive crash countermeasures. The findings of this dissertation are practice ready. Two of the studies were featured by AASHTO as important studies. AASHTO awarded the edge line research as one of the 2014 Sweet Sixteen High Value Research projects. AASHTO featured the research findings of this project in an AASHTO newsletter. AASHTO nominated the lane conversion project as as one of the 2013 Sweet Sixteen High Value Research projects. The research findings of this project were also highlighted in one of the AASHTO newsletters. The transportation authority of Louisiana has considered the recommendations from this research to use them in some of the new projects. The dissertation also plays a role in developing a commercialization tool for selecting effective inexpensive countermeasures.

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APPENDIX A: R CODES

```
### Figure 2.9.

## reading the data
setwd("/my_folder")
uft1 <- read.csv("4u5t1.csv")
uft2 <- read.csv("4u5t2.csv")
uft3 <- read.csv("4u5t3.csv")

LA3025 <- subset(uft1, Control=="LA3025")
LA3025 <- LA3025[c(1:3)]
LA182 <- subset(uft1, Control=="LA182")
LA182 <- LA182[c(1:3)]
LA28 <- subset(uft1, Control=="LA28")
LA28 <- LA28[c(1:3)]
LA1138 <- subset(uft1, Control=="LA1138")
LA1138 <- LA1138[c(1:3)]

## creating plot
library(ggplot2)
p <- ggplot(LA3025)
plot1 <- p +
geom_bar(aes(x=reorder(Type, Crashes),
y= Crashes, fill=Condition),
stat = "identity", position="dodge")+
theme_bw()+
labs(title = "LA_3025") +
ylab("Crash_Frequency")+ xlab("")+
theme(axis.text.x = element_text(angle = 45,
hjust = 1, size=14))+
scale_fill_brewer()


p <- ggplot(LA182)
plot2 <- p +
geom_bar(aes(x=reorder(Type, Crashes),
y= Crashes, fill=Condition),
stat = "identity", position="dodge")+theme_bw()+
```

```
labs(title = "LA_182") +
ylab("Crash_Frequency")+ xlab("")+
theme(axis.text.x =
element_text(angle = 45, hjust = 1, size=14))+
scale_fill_brewer()


p <- ggplot(LA28)
plot3 <- p +
geom_bar(aes(x=reorder(Type, Crashes),
y= Crashes, fill=Condition),
stat = "identity", position="dodge")+
theme_bw()+
labs(title = "LA_28") +
ylab("Crash_Frequency")+ xlab("")+
theme(axis.text.x =
element_text(angle = 45, hjust = 1, size=14))+
scale_fill_brewer()

p <- ggplot(LA1138)
plot4 <- p +
geom_bar(aes(x=reorder(Type, Crashes),
y= Crashes, fill=Condition),
stat = "identity", position="dodge")+theme_bw()+
labs(title = "LA_1138") +
ylab("Crash_Frequency")+ xlab("")+
theme(axis.text.x =
element_text(angle = 45, hjust = 1, size=14))+
scale_fill_brewer()


library(gridExtra)
g_legend<-function(a.gplot){
tmp <- ggplot_gtable(ggplot_build(a.gplot))
leg <- which(sapply(tmp$grobs,
function(x) x$name) == "guide-box")
legend <- tmp$grobs[[leg]]
return(legend)}
```

```
mylegend<-g_legend(plot1)
p3 <- grid.arrange(arrangeGrob(plot1 +
theme(legend.position="none"),
plot2 + theme(legend.position="none"),
plot3 + theme(legend.position="none"),
nrow=2),
mylegend, nrow=2, heights=c(7,1))


### Figure 2.10.
LA3025 <- subset(uft2, Control=="LA3025")
LA3025 <- LA3025[c(1:3)]
LA182 <- subset(uft2, Control=="LA182")
LA182 <- LA182[c(1:3)]
LA28 <- subset(uft2, Control=="LA28")
LA28 <- LA28[c(1:3)]
LA1138 <- subset(uft2, Control=="LA1138")
LA1138 <- LA1138[c(1:3)]

p <- ggplot(LA3025)
plot1 <- p +
geom_bar(aes(Type, Crashes, fill=Condition),
stat = "identity", position="dodge")+theme_bw()+
labs(title = "LA_3025") +
ylab("Crash_Frequency")+ xlab("")+
theme(axis.text.x =
element_text(angle = 0, hjust = 1, size=14))+
scale_fill_brewer()

p <- ggplot(LA182)
plot2 <- p +
geom_bar(aes(Type, Crashes, fill=Condition),
stat = "identity", position="dodge")+theme_bw()+
labs(title = "LA_182") +
ylab("Crash_Frequency")+ xlab("")+
theme(axis.text.x =
element_text(angle = 0, hjust = 1, size=14))+
scale_fill_brewer()
```

```
p <- ggplot(LA28)
plot3 <- p +
geom_bar(aes(Type, Crashes, fill=Condition),
stat = "identity", position="dodge")+theme_bw()+
labs(title = "LA_28") +
ylab("Crash_Frequency")+ xlab("")+
theme(axis.text.x =
element_text(angle = 0, hjust = 1, size=14))+
scale_fill_brewer()


p <- ggplot(LA1138)
plot4 <- p + geom_bar(aes(Type, Crashes, fill=Condition),
stat = "identity", position="dodge")+
theme_bw()+
labs(title = "LA␣1138") +
ylab("Crash_frequency")+ xlab("")+
theme(axis.text.x =
element_text(angle = 0, hjust = 1, size=14))+
scale_fill_brewer()

p3 <- grid.arrange(arrangeGrob(plot1 +
theme(legend.position="none"),
plot2 + theme(legend.position="none"),
plot3 + theme(legend.position="none"),
plot4 + theme(legend.position="none"),
nrow=2),
mylegend, nrow=2, heights=c(7,1))


### Figure 2.11.

LA3025 <- subset(uft3, Control=="LA3025")
LA3025 <- LA3025[c(1:3)]
LA182 <- subset(uft3, Control=="LA182")
LA182 <- LA182[c(1:3)]
LA28 <- subset(uft3, Control=="LA28")
LA28 <- LA28[c(1:3)]
```

```
LA1138 <- subset(uft3, Control=="LA1138")
LA1138 <- LA1138[c(1:3)]

p <- ggplot(LA3025)
plot1 <- p +
geom_bar(aes(Type, Crashes, fill=Condition),
stat = "identity", position="dodge")+theme_bw()+
labs(title = "LA_3025") +
ylab("Crash_Frequency")+ xlab("")+
theme(axis.text.x =
element_text(angle = 90, hjust = 1, size=14))+
scale_fill_brewer()

p <- ggplot(LA182)
plot2 <- p +
geom_bar(aes(Type, Crashes, fill=Condition),
stat = "identity", position="dodge")+theme_bw()+
labs(title = "LA_182") +
ylab("Crash_Frequency")+ xlab("")+
theme(axis.text.x =
element_text(angle = 90, hjust = 1, size=14))+
scale_fill_brewer()

p <- ggplot(LA28)
plot3 <- p +
geom_bar(aes(Type, Crashes, fill=Condition),
stat = "identity", position="dodge")+theme_bw()+
labs(title = "LA_28") +
ylab("Crash_Frequency")+ xlab("")+
theme(axis.text.x =
element_text(angle = 90, hjust = 1, size=14))+
scale_fill_brewer()


p <- ggplot(LA1138)
plot4 <- p +
geom_bar(aes(Type, Crashes, fill=Condition),
stat = "identity", position="dodge")+theme_bw()+
labs(title = "LA_1138") +
```

```
ylab("Crash_Frequency")+ xlab("")+
theme(axis.text.x =
element_text(angle = 90, hjust = 1, size=14))+
scale_fill_brewer()


p3 <- grid.arrange(arrangeGrob(plot1 +
theme(legend.position="none"),
plot2 + theme(legend.position="none"),
plot3 + theme(legend.position="none"),
plot4 + theme(legend.position="none"),
nrow=2),
mylegend, nrow=2, heights=c(7,1))


### Figure 2.15
LA3025_1 <- read.csv("4u5t4.csv")

p <- ggplot(LA3025_1)
plot1 <- p +
geom_bar(aes(Year, Crashes, fill=Condition),
stat = "identity", position="dodge")+
theme_bw()+
labs(title = "LA_3025") +
ylab("Crash_Frequency")+ xlab("")+
scale_x_continuous(breaks=1999:2011)+
theme(axis.text.x =
element_text(angle = 90, hjust = 1, size=14))+
scale_fill_brewer()
plot1


### Figure 3.3

setwd("my_folder")
pavmark <- read.csv("Rana2.csv")

library(vcd)
library(lattice)
```

```
library(ggplot2)

k <- ggplot(pavmark, aes(ADT, ..density..)) +
geom_histogram(binwidth = 500)+
theme_bw()+ylab("Density")+
theme(text = element_text(size=18))
k + facet_grid(. ~ Year)

### Figure 3.4

k <- ggplot(pavmark, aes(EST_SPEED, ..density..)) +
geom_histogram(binwidth = 10)+
theme_bw()+xlab ("Vehicle_Speed") +ylab("Density")+
theme(text = element_text(size=18))
k + facet_grid(. ~ Year)

### Figure 3.5
boysbox <- ggplot(pavmark, aes(Year, EST_SPEED))+
theme_bw()+
ylab("Vehicle_Speed")+
theme(text = element_text(size=18))
boysbox + geom_boxplot()


### Figure 3.9
k <- ggplot(pavmark, aes(CR_HOUR, ..density..)) +
geom_histogram(binwidth = 0.5)+theme_bw()+
xlab("Crash_Hour")+ ylab("Density")+
scale_x_continuous(breaks=1:24)+
theme(text = element_text(size=18))
k + facet_grid(. ~ Year)

### Figure 3.15
p <- ggplot(pavmark,
aes(EST_SPEED, CR_HOUR,  colour =
factor(SEVERITY_CD))) +
geom_point()+xlab("Vehicle_Speed")+
ylab("Crash_Hour")+
theme_bw()+ theme(text = element_text(size=18))
```

```
p + facet_grid(SEVERITY_CD~ Year,
scales = "free", space = "free")

### Figure 3.16
p <- ggplot(pavmark,
aes(EST_SPEED, CR_HOUR,
colour = factor(WEATHER_CD))) +
geom_point()+xlab("Vehicle_Speed")+
ylab("Crash_Hour")+
theme_bw()+
theme(text = element_text(size=18))
p + facet_grid(WEATHER_CD~ Year,
scales = "free", space = "free")


### Figure 4.2
rpmm <- read.csv("RPM.csv")
rpmm

cond1 <- subset(rpmm,
Condition=="Rural_(night_hours)" &
Countermeasure=="RPM_and_Striping")
cond2 <- subset(rpmm,
Condition=="Rural_(24_hours)" &
Countermeasure=="RPM_and_Striping")
cond3 <- subset(rpmm,
Condition=="Urban_(night_hours)" &
Countermeasure=="RPM_and_Striping")
cond4 <- subset(rpmm,
Condition=="Urban_(24_hours)" &
Countermeasure=="RPM_and_Striping")
cond5 <- subset(rpmm,
Condition=="Rural_(night_hours)" &
Countermeasure=="RPM")
cond6 <- subset(rpmm,
Condition=="Rural_(night_hours)" &
Countermeasure=="Striping")
cond7 <- subset(rpmm,
Condition=="Rural_(24_hours)" &
```

```
Countermeasure=="RPM")
cond8 <- subset(rpmm,
Condition=="Rural_(24_hours)" &
Countermeasure=="Striping")
cond11 <- cond1[c(1,4)]
cond21 <- cond2[c(1,4)]
cond31 <- cond3[c(1,4)]
cond41 <- cond4[c(1,4)]
cond51 <- cond5[c(1,4)]
cond61 <- cond6[c(1,4)]
cond71 <- cond7[c(1,4)]
cond81 <- cond8[c(1,4)]

p <- ggplot(cond1)
plot11 <- p +
geom_bar(aes(x=reorder(Rating, CrashRate),
y= CrashRate,fill="white"),
stat = "identity", position="dodge")+theme_bw()+
labs(title = "Rural_(night_hours)") +
ylab("Avg._Crash_Rate")+
xlab("RPM_and_Striping")+
theme(legend.position = "none")+
theme(text = element_text(size=18))+
scale_fill_brewer()

p <- ggplot(cond2)
plot12 <- p +
geom_bar(aes(x=reorder(Rating, CrashRate),
y= CrashRate,fill="white"),
stat = "identity", position="dodge")+theme_bw()+
labs(title = "Rural_(24_hours)") +
ylab("Avg._Crash_Rate")+
xlab("RPM_and_Striping")+
theme(legend.position = "none")+
theme(text = element_text(size=18))+
scale_fill_brewer()

grid.arrange(plot11, plot12,  ncol=2)
```

```
### Figure 4.3
p <- ggplot(cond3)
plot13 <- p +
geom_bar(aes(x=reorder(Rating, CrashRate),
y= CrashRate,fill="white"),
stat = "identity", position="dodge")+theme_bw()+
labs(title = "Urban_(night_hours)") +
ylab("Avg._Crash_Rate")+
xlab("RPM_and_Striping")+
theme(legend.position = "none")+
theme(text = element_text(size=18))+
scale_fill_brewer()

p <- ggplot(cond4)
plot14 <- p +
geom_bar(aes(x=reorder(Rating, CrashRate),
y= CrashRate,fill="white"),
stat = "identity", position="dodge")+theme_bw()+
labs(title = "Urban_(24_hours)") +
ylab("Avg._Crash_Rate")+
xlab("RPM_and_Striping")+
heme(legend.position = "none")+
theme(text = element_text(size=18))+
scale_fill_brewer()

grid.arrange(plot13, plot14,  ncol=2)

### Figure 4.4
p <- ggplot(cond5)
plot15 <- p +
geom_bar(aes(x=reorder(Rating, CrashRate),
y= CrashRate,fill="white"),
stat = "identity", position="dodge")+theme_bw()+
labs(title = "Rural_(night_hours)") +
ylab("Avg._Crash_Rate")+ xlab("RPM")+
theme(legend.position = "none")+
theme(text = element_text(size=18))+
scale_fill_brewer()
```

```
p <- ggplot(cond6)
plot16 <- p +
geom_bar(aes(x=reorder(Rating, CrashRate),
y= CrashRate,fill="green"),
stat = "identity", position="dodge")+theme_bw()+
labs(title = "Rural_(night_hours)") +
ylab("Avg._Crash_Rate")+ xlab("Striping")+
theme(legend.position = "none")+
theme(text = element_text(size=18))+
scale_fill_brewer()

p <- ggplot(cond7)
plot17 <- p +
geom_bar(aes(x=reorder(Rating, CrashRate),
y= CrashRate,fill="yellow"),
stat = "identity", position="dodge")+theme_bw()+
labs(title = "Rural_(24_hours)") +
ylab("Avg._Crash_Rate")+ xlab("RPM")+
theme(legend.position = "none")+
theme(text = element_text(size=18))+
scale_fill_brewer()

p <- ggplot(cond8)
plot18 <- p +
geom_bar(aes(x=reorder(Rating, CrashRate),
y= CrashRate,fill="blue"),
stat = "identity", position="dodge")+theme_bw()+
labs(title = "Rural_(24_hours)") +
ylab("Avg._Crash_Rate")+ xlab("Striping")+
theme(legend.position = "none")+
theme(text = element_text(size=18))+
scale_fill_brewer()

grid.arrange(plot15, plot16, plot17, plot18, ncol=2)


### Twitter Mining
```

```
### TWEET COLLECTION

### Setting up
library(twitteR)
require(twitteR)
require(ROAuth)
requestURL <- "https://api.twitter.com/oauth/request_token"
accessURL <- "https://api.twitter.com/oauth/access_token"
authURL <- "https://api.twitter.com/oauth/authorize"
consumerKey <- "my_consumer_key"
consumerSecret <- "my_consumer_secret"
twitCred <- OAuthFactory$new(consumerKey=consumerKey,
consumerSecret=consumerSecret,
requestURL=requestURL,
accessURL=accessURL,
authURL=authURL)
setwd("my_folder")
download.file(url="http://curl.haxx.se/ca/cacert.pem",
        destfile="cacert.pem")
twitCred$handshake(cainfo="cacert.pem")
registerTwitterOAuth(twitCred)
save(list="twitCred", file="twitteR_credentials")
load("twitteR_credentials")
registerTwitterOAuth(twitCred)

### Data Collection
five_T = searchTwitter("5T␣TWLTL",
        cainfo="cacert.pem", lang= "en", n=3200)
five_T1 <- twListToDF(seatbelt)
write.csv(five_T1, "5t.csv")

RPM = searchTwitter("RPM",
        cainfo="cacert.pem", lang= "en", n=3200)
RPM1 <- twListToDF(RPM)
write.csv(RPM1, "rpm.csv")

edge = searchTwitter("Edge␣line",
        cainfo="cacert.pem", lang= "en", n=3200)
edge1 <- twListToDF(edge)
```

```
write.csv(edge1, "edge.csv")


### Sentiment Score
pos = scan('positive-words.txt', what='character', comment.char=';')
neg = scan('negative-words.txt', what='character', comment.char=';')

pos.words = c(pos, 'upgrade')
neg.words = c(neg, 'wtf', 'wait', 'waiting',
        'epicfail', 'mechanical')
neglist <- c('congestion', 'blocked',
        'accident','delays', 'closed', 'stalled','incident')
poslist <- c('open', 'minimal', 'recovery', 'cleared',
        'clear', 'effective', 'reduction','efficient', )

library(plyr)
library(stringr)

senti_score = function(sentences, pos.words,
        neg.words, .progress='none')
{
scores = laply(sentences, function(sentence,
        pos.words, neg.words) {
sentence = gsub('[[:punct:]]', '', sentence)
sentence = gsub('[[:cntrl:]]', '', sentence)
sentence = gsub('\\d+', '', sentence)
sentence = tolower(sentence)
word.list = str_split(sentence, '\\s+')
words = unlist(word.list)
pos.matches = match(words, pos.words)
neg.matches = match(words, neg.words)
pos.matches = !is.na(pos.matches)
neg.matches = !is.na(neg.matches)
pos.matches1 = match(words, poslist)
neg.matches1 = match(words, neglist)
pos.matches1 = !is.na(pos.matches1)
neg.matches1 = !is.na(neg.matches1)
score = sum(pos.matches) + 2*sum(pos.matches1)-
(sum(neg.matches)+2*sum(neg.matches1))
```

```
return(score)
}, pos.words, neg.words, .progress=.progress )
scores.df = data.frame(score=scores,
        text=sentences)
return(scores.df)
}


### Figure 5.5

a1.text <- read.csv("5t.csv" )
a1.scores = senti_score(a1.text$text,
        pos.words, neg.words, .progress='text')
plot1 <- qplot(a1.scores$score)
plot11 <- plot1 +xlab("Score") +
ylab("No.␣of␣Tweets")+theme_bw()+
scale_x_continuous(breaks=-5:5)+
labs(title = "Search␣term:␣5T␣TWLTL")

a2.text <- read.csv("edge.csv")
a2.scores = senti_score(a2.text$text,
        pos.words, neg.words, .progress='text')
plot2 <- qplot(a2.scores$score)
plot21 <- plot2 +xlab("Score") +
ylab("No.␣of␣Tweets")+theme_bw()+
scale_x_continuous(breaks=-5:5)+
labs(title = "Search␣term:␣Edge␣line")

a3.text <- read.csv("rpm.csv")
a3.scores = senti_score(a3.text$text,
        pos.words, neg.words, .progress='text')
plot3 <- qplot(a3.scores$score)
plot31 <- plot3 +xlab("Score") +
ylab("No.␣of␣Tweets")+theme_bw()+
scale_x_continuous(breaks=-5:5)+
labs(title = "Search␣term:␣RPM")


library(gridExtra)
```

```
grid.arrange(plot11, plot21, plot31, ncol=1)
```

APPENDIX B: LIST OF ABBREVIATIONS

AADT Annual Average Daily Traffic

AASHTO American Association of State Highway and Transportation Officials

CMF Crash Modification Factor

CPI Cost Performance Indicator

DMADV Define-Measure-Analyze-Design-Verity

DMAIC Define-Measure-Analyze-Improve-Control

DOTD Louisiana Department of Transportation and Development

EB Empirical Bayes

EDA Exploratory Data Analysis

FHWA Federal Highway Administration

HSM Highway Safety Manual

LTRC Louisiana Transportation Research Center

MAP-21 Moving Ahead for Progress in the 21st Century Act

MPO Metropolitan Planning Organization

MUTCD Manual on Uniform Traffic Control Devices

NCHRP National Cooperative Highway Research Program

NHTSA National Highway Transportation Safety Administration

PDO Property Damange Only

ROR Run Off Road

RPM Raised Pavement Markers

RTM Regression To Mean

SASHTO Southeastern Association of State Highway and Transportation Officials

SPF Safety Performance Function

TWLTL Two Way Left Turn Lane

SHSP Strategic Highway Safety Plan

SIPOC suppliers, inputs, process, outputs, and customers

VMT Vehicle Miles Traveled

VOC Voice of Customer

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ABSTRACT

Highway safety improvement is a critical issue for local and national transportation authorities. One of the most important tasks in highway safety analysis is the identification of appropriate countermeasures that might be useful in making significant safety improvement. Targeting safety at roadway segments has been the key focus of safety related projects at all levels. Recognizing that resources are limited in Louisiana, an emphasis is provided on the identification of strategies that will yield effective results that are easily implemented from both time and cost perspective. An extensive study on the selection of Louisiana specific inexpensive and effective countermeasures has not been performed yet. Safety countermeasures with high safety effects and low implementation costs are always preferable. This dissertation has developed a Six Sigma DMADV tool uniquely designed for determining effective, inexpensive countermeasures that can be used in both aggregate and disaggregate level. Using the framework of DMADV toolset, this dissertation has selected three effective inexpensive countermeasures suitable for Louisiana and has developed CMFs for the selected countermeasures. Moreover, a precise commercialization tool has been developed for transferring the research results to successful commercial product design. The results from this dissertation are practice-ready and has been used by the transportation authorities in Louisiana.

BIOGRAPHICAL SKETCH

Subasish Das received his Bachelor of Science in 2007 in Civil Engineering from Bangladesh University of Engineering and Technology (BUET) in Dhaka, Bangladesh. After working two years in Bangladesh and the United Arab Emirates, he pursued graduate studies at the University of Louisiana at Lafayette. Subasish applied for doctoral candidacy after receiving his Master of Science in Civil Engineering in 2012. He completed the requirements for this Doctor of Philosophy in Systems Engineering (Civil Engineering Concentration) from the University of Louisiana at Lafayette in the summer of 2015. Subasish has been awarded a number of awards for his excellence in transportation safety research: 2015 Eno fellowship, 2014 and 2013 Gulf Region Intelligent Transportation Systems award, 2014 SASHTO outstanding student award, and 2014 AASHTO Sweet Sixteen High Value Research Award.