Converting Four lane roadways into Five lane roadways on Urban structure: Study on Safety Effectiveness

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ABSTRACT

In urban or suburban areas with large number of access points, four-lane undivided highways are prone to crashes due to left-turning and through movements in a single lane. Expensive countermeasures like conversion from undivided to divided road are recommended by many studies. One inexpensive alternative is reconfiguring the existing roadways by either increasing or decreasing the number of lanes. This study investigated the safety impact of converting four lane undivided roadways (4U) to five lane undivided roadways (5T) with a two-way left-turn lane (TWLTL). This study used Empirical Bayes method to determine the safety impact of this inexpensive countermeasure. In this study, data from eight treatment sites from Louisiana were collected for investigation and site-specific Crash Modification Factor (CMF) values were calculated. Although, 5T is usually not preferable due to its exposure of higher number of crashes in the existing literature, the findings of the current study indicated a positive safety impact. The benefit-cost ratio of this conversion ranges from 97 to 379. The current findings indicate that 4U to 5T is a feasible and inexpensive solution for urban structure.

INTRODUCTION

Four-lane undivided highways in urban and suburban area become more crash prone with the increase of traffic volume and turning movements. Since the inside lane is used by both high speed through traffic and slow speed left turning traffic, rear-end crashes occur as a result of speed differentials or, in some cases, stopped cars in the active travel lane. Due to increases in roadside development in urban and suburban areas, it is a challenge for transportation engineers and safety specialists to improve the safety of four-lane undivided highways. 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 (LADOTD). Ninety-three percent of these roadways are in urban and suburban areas. A total 8,498 crashes occurred on urban four-lane undivided highways in 2014, where 40 percent of the crashes are rear-end crashes.

The desirable option to improve safety performance is installing physical separation either by barrier or by green space (boulevard). The key constraint to the countermeasure is that it requires significant resources. Converting four-lane undivided urban highway (4U) to a five lane highway (5T) with a two way left turn lane (TWLTL) by restriping is one low-cost solution to the problem. A TWLTL separates turning vehicles from through vehicles without reducing the capacity. However, this lane conversion is not a very popular solution. Louisiana has policies that discourage the five lane highway design with TWLTL in the construction of new roads. This study aims to investigate the safety impact of this inexpensive countermeasure (4U to 5T) to identify possible scopes.

LITERATURE REVIEW

There are very few studies on the safety benefits of this particular type of lane conversion. The AASHTO *Highway Safety Manual (1)* documented several crash modification factors (CMF) but did not provide any crash modification factor (CMF) to evaluate the effectiveness of this reconfiguration to any type of roadways. The TRB Access Management Manual *(2)* and NCHRP Report 420 *(3)* include access management issues like TWLTL thresholds. A National Cooperative Highway Research Program (NCHRP) report stated 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 percent *(4)*. This study was further reinforced by a collision study which reported at least 50 percent less rear-end crash proportion in five lane TWLTL than rear-end crash proportion in four-lane undivided highway *(5)*. One study in Louisiana estimated CMF *(6)* for converting a four-lane undivided highway to a five lane highway to be 0.60, which indicates a 40 percent crash reduction due to this countermeasure implementation.

Since there is limited literature regarding this conversion, the comparison between four-lane undivided highway and five-lane highway with TWLTL under same condition is another approach to explore its safety benefits. The Minnesota Statewide Urban Design and Specifications (2010) *(7)* lists the crash rate of 6.75 for four-lane undivided roadway and 4.01 for five-lane with center turn lane. The results were based on a Minnesota study estimated statewide crash rate of urban four-lane undivided highway with no left turn lane as 5.3 per million vehicle miles traveled and urban four-lane undivided highway with TWLTL as 4.6 per million vehicle miles traveled *(8)*.

A comparison was made between four-lane undivided roadway and five-lane with TWLTL roadway to see the design alternatives in Oklahoma in 2007. It was found that five-lane with TWLTL roadway are more advantageous in reducing rear-end and head on crashes compared to four-lane undivided roadway. This comparison was used to evaluate US 81 for improvement along an approximate 30-mile segment *(9)*, although safety benefit was not one of the key criteria.

In recent years, there were many studies on conversion of urban four-lane to three-lane roadway with a TWLTL in the center. This conversion is also known as “road diet”. This conversion has a proven safety records with some limitations. According to Federal Highway Administration (FHWA) *(10)*, this conversion is suitable for Annual Average Daily Traffic (AADT) less than 20,000. Some studies reported, an increase in rear-end crashes due to speed differential in through traffic and right turn traffic, increased delay and increased travel time. In the city of Grand Rapids, Michigan, it has been reported that, after road diet, rear-end crashes nearly tripled after installation with longer travel times (average increase of 19 to 52 seconds through corridor) and additional delay *(11)*. All these limitations can apparently be overcome by four-lane to five-lane with TWLTL conversion, since it utilizes the road width to accommodate left turn lane, through lane, and right turn lane.

SELECTED SITES

The research team selected eight sites from Louisiana to perform this analysis. TABLE 1 lists the key features from the selected sites.

TABLE 1 Site Information

Sites	**Roadway**	**Parish**	**District**	**Length (mile)**
Site 1	LA 14	Lafourche	2	0.25
Site 2	LA 14	Lafourche	2	0.42
Site 3	LA 14	Vermilion	3	0.47
Site 4	LA 14 Bypass	Vermilion	3	0.67
Site 5	LA 3025	Lafayette	3	1.23
Site 6	LA 182	St. Landry	3	0.15
Site 7	LA 28	Rapides	8	0.40
Site 8	LA 1138	Calcasieu	7	0.79

One key issue in this current countermeasure is the reduction of the lane widths. FIGURE 1 illustrates the roadway sections of the sites (the distances are not measured to scales).

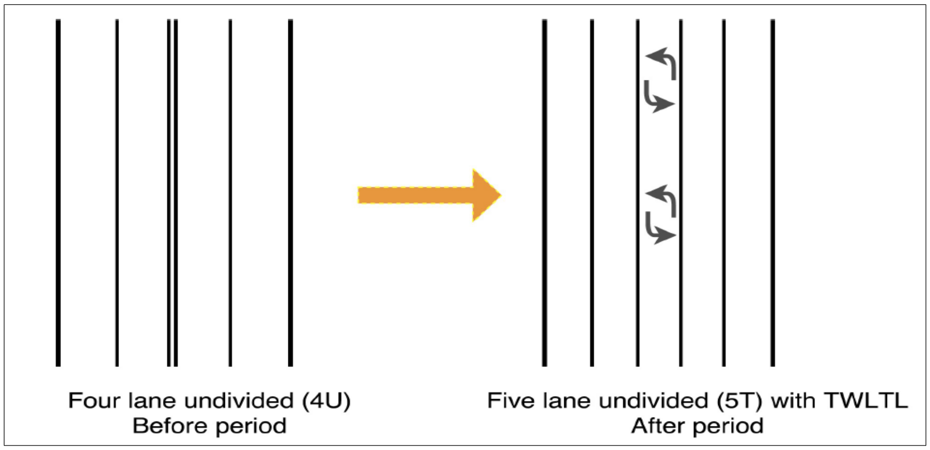

FIGURE 1 Schematic Roadway Sections

TABLE 2 lists the AADT and observed crashes in the before and after years for the sites.

TABLE 2 AADT and observed crashes in before and after years

Sites	Before Period			After Period		
	Years	AADT (vpd)	Total Crashes	Years	AADT (vpd)	Total Crashes
Site 1	2004-2006	19,867	21	2008-2010	19,767	9
Site 2	2004-2006	19,867	118	2008-2010	19,767	47
Site 3	2008-2010	6,833	39	2012-2014	7,900	20
Site 4	2008-2010	19,200	126	2012-2014	21,000	114
Site 5	2000-2002	23,888	358	2004-2006	26,580	148
Site 6	2004-2006	21,367	65	2008-2010	21,100	51
Site 7	2002-2004	27,467	116	2006-2008	27,000	75
Site 8	1996-1998	14,693	115	2000-2002	14,967	79

SAFETY EFFECTIVENESS

The objective of the empirical Bayes methodology is to estimate the number of crashes that would have occurred at an individual treated site in the after period had a treatment not been implemented. This method accounts for the effect of regression-to-the-mean, changes in traffic volume, and other potential changes in the roadway features during the before and after time periods *(14)*. In accounting for regression-to-the-mean, the number of crashes expected in the before period without the treatment ($N_{predicted,\ t,\ b}$) is a weighted average of information from two sources *(12):*

- The number of crashes observed in the before period at the treated sites ($N_{observed,\ t,\ b}$).
- The number of crashes predicted at the treated sites based on reference sites with similar traffic and physical characteristics ($N_{predicted,\ t,\ b}$).

To estimate the weights and the number of crashes expected on sites with similar traffic and physical characteristics, safety performance function (SPF) for 4U and 5T were used. An SPF is a statistical model that predicts the mean crash frequency for similar locations with the same characteristics. These characteristics typically include traffic volume and may include other variables such as traffic control and geometric characteristics. This SPF is used to derive the second source of information for the empirical Bayes estimation- the number of crashes predicted at treated sites based on sites with similar operational and geometric characteristics ($N_{predicted,\ t,\ b}$). The calculation method of this current followed the steps used in Hauer's study *(13).*

Step 1: Evaluate the predictive values
The predictive models for urban and suburban arterial roadway segments are presented in the following equations in the HSM:

$$N_{predicted} = C_L \times (N_{rs} + N_{ped} + N_{bike}) \tag{1}$$

$$N_{rs} = N_{spf\ rs} \times (CMF_1 \times \ldots \times CMF_n) \tag{2}$$

$$N_{spf\ rs} = N_{sv} + N_{mvnd} + N_{mvd} \tag{3}$$

Where:
$N_{predicted}$ = predicted average crash frequency of an individual roadway segment for the selected year;
N_{rs} = predicted average crash frequency of an individual roadway segment (excluding vehicle-pedestrian and vehicle-bicycle collisions);
$N_{spf\ rs}$ = predicted total average crash frequency of an individual roadway segment for base conditions (excluding vehicle-pedestrian and vehicle-bicycle collisions);
N_{ped} = predicted average crash frequency of vehicle-pedestrian collisions for an individual roadway segment;
N_{bike} = predicted average crash frequency of vehicle-bicycle collisions for an individual roadway segment;
$CMF_1 \times \ldots \times CMF_n$= crash modification factors for roadway segments;
C_L = calibration factor for urban and suburban roadway segments in Louisiana.
N_{sv} = predicted average crash frequency of single-vehicle crashes for base conditions;
N_{mvnd} = predicted average crash frequency of multiple-vehicle non-driveway collisions for base conditions;
N_{mvd} = predicted average crash frequency of multiple-vehicle driveway-related collisions.
The SPF for single vehicle crashes and multiple-vehicle non-driveway collisions use the following equation

$$N_{sv} = exp^{a+b\times\ln(AADT)+\ln(L)} \tag{4}$$

$$N_{mvnd} = exp^{a+b\times\ln(AADT)+\ln(L)} \tag{5}$$

Where:
$AADT$ = average annual daily traffic volume (vehicles/day) on roadway segment;
L = length of roadway segment (mi); and
a, b = regression coefficients (from the HSM Table 12-3, and Table 12-5).

The total number of multiple-vehicle driveway-related collisions within a roadway segment is determined as:

$$N_{mvd} = \sum_{\substack{all\\driveway\\types}} n_i \times N_i \times \left(\frac{AADT}{15{,}000}\right)^t \tag{6}$$

Where:

N_i = Number of driveway-related collisions per driveway per year for driveway type i from

n_i = number of driveways within roadway segment of driveway type i including all driveways on both sides of the road (shown in

); and

t = coefficient for traffic volume adjustment from TABLE 3

TABLE 3 Driveway densities in each sites

Driveway Type	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7	Site 8	t for 4U	t for 5T
Major Commercial	0	0	0	0	0	0	0	1	0.182	0.165
Major Residential	0	1	0	1	0	0	0	0	0.096	0.087
Major Industrial	0	0	0	0	0	0	0	0	0.198	0.181
Minor Commercial	11	15	15	29	24	5	28	50	0.058	0.053
Minor Residential	0	0	19	5	30	8	2	2	0.018	0.016
Minor Industrial	0	1	0	0	0	0	0	0	0.026	0.024

The research team has consider other CMFs as 1 to determine N_{rs}.

$$N_{rs} = N_{spf\ rs} \times (1 \times \ldots \times 1) = N_{sv} + N_{mvnd} + N_{mvd} \tag{7}$$

C_L value is considered as 1 in this current study.

$$N_{predicted} = 1 \times \left(N_{rs} + N_{ped} + N_{bike}\right) = N_{rs} + N_{ped} + N_{bike} \tag{8}$$

The number of vehicle-pedestrian collisions per year for a roadway segment is estimated as:

$$N_{ped} = N_{rs} \times f_{ped} \tag{9}$$

Where:

f_{ped} = pedestrian crash adjustment factor (from the HSM Table 12-8).

The number of vehicle-bicycle collisions per year for a roadway segment is estimated as:

$$N_{bike} = N_{rs} \times f_{bike} \tag{10}$$

Where:

f_{bike} = pedestrian crash adjustment factor (from the HSM Table 12-9).

TABLE 4 lists the predicted and expected values of the crashes from this method.

TABLE 4 Predicted and Expected values using EB method

Sites	Observed Crashes before years $N_{observed,\ t,\ b}$	Observed Crashes after years $N_{observed,\ t,\ a}$	Predicted Crashes before years $N_{predicted,\ t,\ b}$	Predicted Crashes after years $N_{predicted,\ t,\ a}$	Expected Crashes before years $N_{expected,\ t,\ b}$	Expected Crashes after years $N_{expected,\ t,\ a}$	Variance Var $(N_{expected,\ t,\ a})$
Site 1	21	9	2.24	2.95	13.51	17.85	13.79
Site 2	118	47	3.64	4.85	83.82	111.54	103.59
Site 3	39	20	1.47	2.19	21.00	31.27	23.79
Site 4	126	114	6.72	8.73	103.28	134.18	140.54
Site 5	358	148	14.04	18.27	323.00	420.40	490.79
Site 6	65	51	1.61	2.07	33.30	42.67	27.14
Site 7	116	75	6.43	7.86	93.23	113.98	110.00
Site 8	115	79	6.08	7.99	92.73	121.86	126.81

Step 2: Evaluate the expected values
The empirical Bayes estimate of the expected number of crashes without treatment, $N_{expected,\ t,\ b}$, is computed from the following equation:

$$N_{expected,\ t,\ b} = w \times N_{predicted,\ t,\ b} + (1 - w) \times N_{observed,\ t,\ b} \tag{11}$$

$$w = \frac{1}{1 + k \times \sum_{\substack{all\ study\\ years}} N_{predicted}} \tag{12}$$

Where:
w = weighted adjustment to be placed on the predictive model estimate; and
k = overdispersion parameter of the associated SPF used to estimate $N_{predicted}$

It is important to note that with the increment of over dispersion parameter, the weighted adjustment factor decreases; thus, more emphasis is placed on the observed/reported crashes rather than the SPF predicted crash frequency.

The adjusted value of the empirical Bayes estimate, $N_{expected,\ t,\ a}$, is the expected number of crashes in the after period without treatment and is calculated from the following equation:

$$N_{expected,\ t,\ a} = N_{expected,\ t,\ b} \times \frac{N_{predicted,\ t,\ a}}{N_{predicted,\ t,\ b}} \tag{13}$$

The variance of $N_{expected,\ t,\ a}$:

$$Var(N_{expected,\ t,\ a}) = N_{expected,\ t,\ a} \times \frac{N_{predicted,\ t,\ a}}{N_{predicted,\ t,\ b}} \times (1 - w) \tag{14}$$

Step 3: Evaluate the CMF and variance of CMF:
The CMF and its variance can be calculated from the following equations:

$$CMF = \frac{\dfrac{N_{observed,\ t,\ a}}{N_{expected,\ t,\ a}}}{1 + \dfrac{Var(N_{expected,\ t,\ a})}{N_{expected,\ t,\ a}{}^{2}}} \tag{15}$$

$$Var(CMF) = CMF^2 \frac{\frac{1}{N_{observed,\ t,\ a}} + \frac{Var(N_{expected,\ t,\ a})}{N_{expected,\ t,\ a}{}^2}}{\left[1 + \frac{Var(N_{expected,\ t,\ a})}{N_{expected,\ t,\ a}{}^2}\right]^2} \qquad (16)$$

TABLE 5 enlists the values of site specific CMF, standard deviations, and 95% confidence interval (CI) of the CMF from this method. The CMF values range from 0.35 to 0.84 (except site 6; in which CMF is greater than 1). The 95% values are lower than 1 in most cases except in site 4, and site 6.

TABLE 5 CMF and variance of CMF values

Sites	CMF	$Var(CMF)$	$sd(CMF)$	$95\%\ CI\ of\ CMF$
Site 1	0.48	0.03	0.18	(0.13, 0.84)
Site 2	0.42	0.01	0.07	(0.28, 0.56)
Site 3	0.62	0.03	0.17	(0.3, 0.95)
Site 4	0.84	0.01	0.11	(0.63, 1.05)
Site 5	0.35	0.00	0.03	(0.28, 0.42)
Site 6	1.18	0.05	0.22	(0.76, 1.6)
Site 7	0.65	0.01	0.10	(0.47, 0.84)
Site 8	0.64	0.01	0.09	(0.46, 0.82)

FIGURE 2 shows SPF graphics for multiple vehicle non-driveway crashes. A similar graphic (see FIGURE 3) for different driveway densities was reproduced by Das (*15*). In both cases, predicted crashes for 5T are higher in numbers. However, this study shows different results.

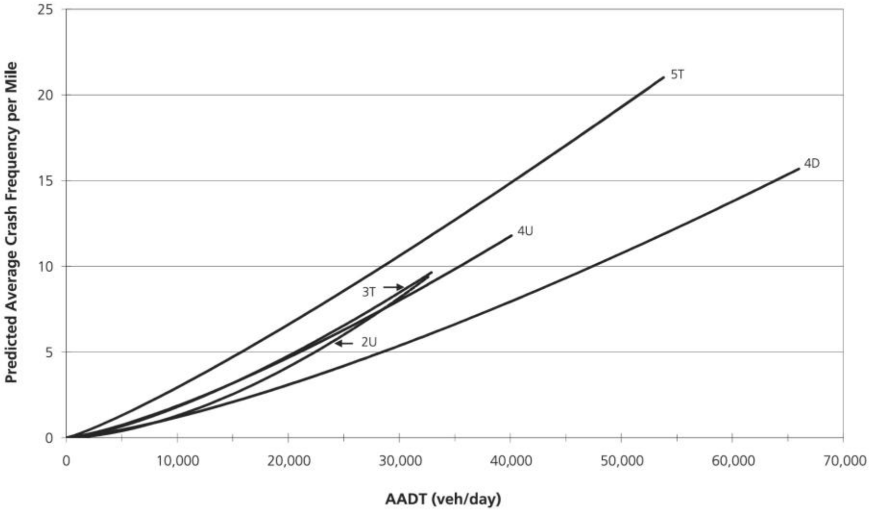

FIGURE 2 SPF graphics for multiple vehicle non-driveway collisions (Source: *1*)

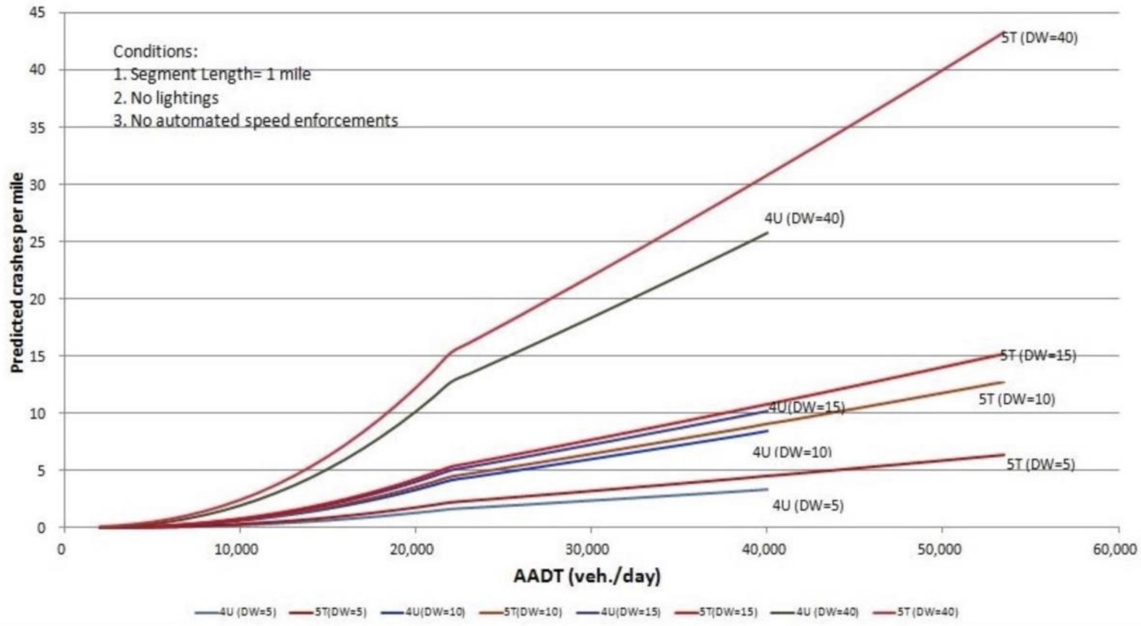

FIGURE 3 Multiple-vehicle driveway-related predicted crashes per mile (Source: *15*)

BENEFIT COST ANALYSIS

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. To determine the recent cost per injury or PDO crashes, study by Sceneider is consulted *(16).* In that study, cost estimates are based on a study conducted by NHTSA in 2000 and these values were adjusted by the Cost Performance Index (CPI) to obtain costs for 2014. The benefit cost ratio for the treatment sites range from 97 to 379. The benefit-cost ratios are shown in TABLE 6.

TABLE 6 Benefit Cost Ratios

Site	Total Benefits ($)	Total Cost ($)	B/C Ratio
Site 1	278,951	2,863	97
Site 2	1,387,818	4,809	289
Site 3	810,675	5,382	151
Site 4	1,142,767	7,672	149
Site 5	3,039,771	14,084	216
Site 6	651,252	1,718	379
Site 7	630,598	4,580	138
Site 8	1,076,223	9,046	119
PDO crash cost($)	6,623		
Injury Crash cost ($)	46,518		
Cost per mile ($)	11,450		

CONCLUSION

The study demonstrates that 4U to 5T conversion on urban roads can be very beneficial. Empirical Bayes Analysis shows an expected crash reduction up to 52% with only one site with possible crash increase. The benefit-cost ratio is very promising (ranges from 97 up to 379). 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. This study suggests that inserting a two way left turn lane on four lane undivided urban highways can have significant benefit. Conversion to divided roadways is very effective crash countermeasure. With available funds in the future, it is easy to convert these five-lane roadway segments to a boulevard roadway type- an effective but expensive and time-consuming countermeasure. However, it is also important to note that one-size-fits-all solutions do not usually work in highway safety issues. Caution must be taken when applying this crash countermeasure (4U to 5T) in other locations.

REFERENCES

1. *Highway safety manual*. American Association of State Highway and Transportation Officials, Washington, D.C., 2010.
2. *Access management manual, 2nd Edition*. Transportation Research Board, Washington, DC, 2014.
3. Gluck, J., H. S. Levinson, and V. Stover. NCHRP 420: *Impacts of access management techniques*. TRB, Washington, DC, 1999.
4. Harwood D. Effective Utilization of Street Width on Urban Arterials. *Transportation Research Board*: *Journal of the Transportation Research Board*. Vol 330, 1990, pp. 27-28.
5. McCormick D. and E. Wilson. Comparing Operational Effects of Continuous Two-Way Left-Turn Lanes (Abridgment). *Transportation Research Board*: *Journal of the Transportation Research Board*. Vol. 923, 1983, pp. 86-90.
6. Sun X. and S. Das. Developing Louisiana Crash Reduction Factors. Report No.: FHWA/LA.12/506, 2013.
7. Iowa Department of Transportation. Minnesota Statewide Urban Design and Specifications. Ch. 5, Sec. I. 2010. http://www.iowadot.gov/design/dmanual/manual.html?reload .Accessed: July 2016.
8. Preston H., R. Newton, D. Keltner and C. Albercht. Statistical Relationship between Vehicular Crashes and Highway Access. BRW, Incorporated and Minnesota Department of Transportation, 1999, pp. 28-42.
9. Oklahoma Department of Transportation. US 81 Corridor Study from North of Union City South to SH 19 South of Chickasha. App. H. 2007. http://www.okladot.state.ok.us/p-r-div/us81corridor/.Accessed: July 2016.
10. U.S. Department of Transportation. Federal Highway Administration. Evaluation of Lane Reduction “Road Diet” Measures on Crashes. 2010.
11. U.S. Department of Transportation. Federal Highway Administration. Road diet Case Studies. PUBLICATION: FHWA-SA-15-052. http://safety.fhwa.dot.gov/road_diets/case_studies/ .Accessed: July 2016.
12. Gross, F., B. Persaud, and C. Lyon. A Guide to Developing Quality Crash Modification Factors U.S. Dept. of Transportation, Federal Highway Administration, Office of Safety, Washington, D.C.. Report No. FHWA-SA-10-032, December, 2010.
13. Hauer, E. *Observational before--after studies in road safety: estimating the effect of highway and traffic engineering measures on road safety*. Pergamon, Oxford, OX, U.K., 1997.

14. Sun, X., S. Das, Z. Zhang, F. Wang, and C. Leboeuf. Investigating Safety Impact of Edgelines on Narrow, Rural Two-Lane Highways by Empirical Bayes Method. *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 2433, 2014, pp.121–128.
15. Das, S. Effectiveness of Inexpensive Crash Countermeasures to Improve Traffic Safety. July, 2015.
16. Schneider, H. Louisiana Traffic Records Data Report 2014. Highway Safety Research Group, 2015.