Reconfiguring Urban Undivided Four-Lane Highways to Five-Lane: A Nonideal but Very Effective Solution for Crash Reduction

M. Ashifur Rahman, A.M.ASCE[1]; Xiaoduan Sun, Ph.D.[2]; and Subasish Das, Ph.D.[3]

Abstract: Although a reconfiguration to three-lane with a left turn lane remains the most prevalent cost-effective countermeasure, some four-lane undivided highway segments in Louisiana have been reconfigured to five-lane segments with a left-turn lane by utilizing the existing pavement width basically at the cost of restriping. The current study analyzes nine locations where undivided four-lane roadways were converted to five-lane roadways in Louisiana urban areas with up to 7 years of before-and-after crash data. To avoid any potential regression-to-the-mean bias, the empirical Bayes (EB) method was used with the safety performance function (SPF) developed by the Louisiana Department of Transportation and Development (LaDOTD). Despite the contemplation in design guidelines and previous studies that a five-lane roadway is more crash-susceptible than a four-lane roadway, the safety effectiveness of conversion to five-lane was deduced to be significantly positive. Consistent crash reduction was observed in all sites, which resulted in a crash modification factor (CMF) of 0.48 with a small variance of 0.001. Expectedly, a substantial reduction in the target crash type, rear-end crashes, was achieved. This four-lane to five-lane conversion was found very effective specifically for urban and suburban roadways with annual average daily traffic (AADT) ranging from 15,000 to 30,000 and driveway density from 18 to 31 driveways per kilometer (30–50 driveways per mile). The high safety benefit-cost ratio, 78:1, indicates strong support to use this countermeasure on four-lane undivided roadways with additional evaluation for feasibility. **DOI: 10.1061/JTEPBS.0000422.** *© 2020 American Society of Civil Engineers.*

Author keywords: Urban four-lane highway; Five-lane highway; Inexpensive countermeasure; Left-turn lane; Highway safety.

Downloaded from ascelibrary.org by Texas A&M University on 08/01/20. Copyright ASCE. For personal use only; all rights reserved.

Introduction

Four-lane undivided highways (4U) in urban and suburban areas are commonly prone to rear-end and left-turn crashes due to speed differentials caused by left-turning vehicles with through vehicles. The crash-susceptibility of undivided four-lane highways is particularly prevalent in areas with a high density of driveways. According to the Louisiana *Highway Section Database* (LaDOTD 2015), the state has about 402 km (250 mi) of urban four-lane undivided highways, which is 1.6% of the total state-controlled road network. Between 2011 and 2015, approximately 45,000 crashes occurred on the four-lane undivided highways, which accounted for 9% of the total crashes in the state during the same period. Among these crashes, 30% resulted in injuries, the major crash types of which were rear-end (40%), right-angle (24%), and left-turn (15%) crashes.

To mitigate rear-end and right-angle crashes in areas with strip development, separating left-turn vehicles from through traffic by reconfiguring the undivided four-lane roadway to a three-lane roadway (3T) with a two-way left-turn lane in the middle is the most common inexpensive countermeasure, which basically involves the cost of restriping. The three-lane configuration can utilize additional space for nonmotorized travel modes or on-street parking, creating an opportunity for a complete street environment. Conversion to three lanes is being recognized as a better and safer alternative design compared with undivided four-lane roadways while maintaining the highway functions. The three-lane roadways with two-way left-turn lane inherently possess less midblock conflict points, less crossing and through traffic conflict points at intersections, and better sight distance for vehicles taking left turns (Welch 1999). However, 3T conversion has been recommended for annual average of daily traffic (AADT) only up to 20,000 to avoid congestion (Huang et al. 2002).

Conversion to a five-lane roadway (5T), consisting of two through lanes in both directions with a two-way left-turn lane in the middle, by restriping is another alternative to a conventional undivided four-lane roadway aimed at separating the left-turn lane without sacrificing the roadway capacity. In the AASHTO design guidelines, 5T has been identified as a practical solution for arterial highways passing through a developed area with numerous cross streets and driveways rather than setting up multiple storage bays for left-turning traffic (AASHTO 2018). Conversion from 4U to 5T typically utilizes the full width of the pavement and reduces lane width to provide a two-way left-turn lane in the middle without occupying the additional right of way. Fig. 1 illustrates before and after images of a typical 4U to 5T conversion (Knapp et al. 2014).

The 5T is considered nonideal because it often takes almost total width of the pavement without dedicating any space for through movement facilities for nonmotorized travel modes (i.e., pedestrians and bicycles). At intersections, pedestrians and bicyclists from intersecting roadways are forced to cross more lanes. It also perpetuates strip development specifically on urban arterials and hence is

[1]Ph.D. Candidate, Dept. of Civil Engineering, Univ. of Louisiana at Lafayette, Lafayette, LA 70504 (corresponding author). ORCID: https://orcid.org/0000-0001-6940-1599. Email: ashifur@louisiana.edu

[2]Professor, Dept. of Civil Engineering, Univ. of Louisiana at Lafayette, Lafayette, LA 70504. Email: xsun@louisiana.edu

[3]Associate Transportation Researcher, Texas A&M Transportation Institute, Texas A&M Univ. System, 3135 TAMU, College Station, TX 77843. Email: s-das@tti.tamu.edu

Note. This manuscript was submitted on February 28, 2019; approved on May 4, 2020; published online on July 28, 2020. Discussion period open until December 28, 2020; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Transportation Engineering, Part A: Systems***, © ASCE, ISSN 2473-2907.

Downloaded from ascelibrary.org by Texas A&M University on 08/01/20. Copyright ASCE. For personal use only; all rights reserved.

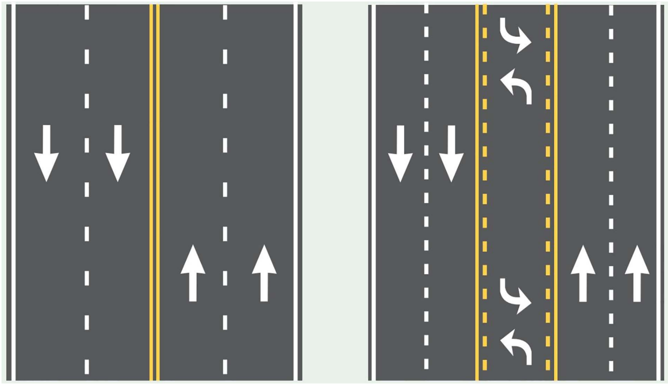

Fig. 1. Before–after image of a typical 4U to 5T reconfiguration.

not often preferable if mobility is prioritized over accessibility. Although Louisiana has about 370 km (230 mi) of 5T, the current design policies for urban roadway discourage 5T for new construction or reconstruction. The 5T is not recommended in the Louisiana minimum design guidelines for urban arterial highways and requires the chief engineer's additional approval if designed (LaDOTD 2009). However, due to the budgetary constraints and the urgent needs to reduce crashes on 4U roadways, more roadway segments in urban and suburban areas have still been converted to 5T in Louisiana.

Very few studies are available on the safety impact of this 4U to 5T conversion, although numerous case studies can be found showing the reduction in total crashes and target crashes due to the 3T road diet implementation (FHWA 2017). The *Road Diet Informational Guide* (Knapp et al. 2014) documents 5T as an additional roadway configuration option for 4U and suggests implementing it specifically for higher capacity purposes. In 2007, the Oklahoma Department of Transportation (ODOT) performed a US-81 corridor study with one of the aims being to identify proposed build alternatives in terms of projected future traffic. The 5T was construed as a cost-effective alternative to reduce crashes generated from left-turning vehicles. It was also deduced that 5T can be considered as a preferred alternative in areas with high driveway density e.g., 28 driveways per kilometer (45 driveways per mile) together on both sides. The 5T was deemed advantageous for AADT between 10,000 and 25,000 with a significant number of left-turning vehicles (ODOT 2007).

Crash modification factor (CMF) Clearinghouse, a repository of crash modification factors of countermeasures (CMF Clearinghouse 2018), currently mentions only one previous study (Sun et al. 2012) on this topic. This was the first comprehensive research on the 4U to 5T conversions for safety, in which four sites were thoroughly investigated using the Improved Prediction method by adjusting traffic volume. The project technical report (Sun and Das 2013) listed the CMFs and standard deviations (in parentheses) from the four sites as 0.45 (0.051), 0.43 (0.062), 0.47 (0.062), and 0.65 (0.075), respectively.

Due to a lack of literature regarding the 4U to 5T conversion, one approach is to compare the performance of 4U and 5T. Based on the current *Highway Safety Manual* (HSM) (e.g., Figs. 12-3, 12-4, 12-7, and 12-9 of the HSM), under the same AADT within the application range, 5T would have a higher number of predicted annual crashes than the undivided four-lane roadways (AASHTO 2010). In Louisiana, the average nonintersection crash rate of 5T is 2.4 per million vehicle kilometers (3.87 per million vehicle miles), whereas 4U has an average nonintersection crash rate of 2.64 per million vehicle kilometers (4.25 per million vehicle miles) (LaDOTD 2016a). The results of the previous study on 4U to 5T conversion in Louisiana also directly contradict the HSM concept. Because this type of reconfiguration is considered nondeal but has performed well in terms of safety improvements, the research team put together information on sites converted in the later years with sites of the previous study to analyze using a more sophisticated approach like empirical Bayes (EB). Specifically, the objectives of this study were to

- develop the corresponding unbiased CMF by using the EB method,
- conduct before-and-after crash analysis for the 4U to 5T lane conversions, and
- estimate the benefit-and-cost ratio to justify the conversion economically.

Methodology

Data

The 4U to 5T reconfiguration in Louisiana basically required removal of old pavement markings and then the application of new pavement markings according to the new dimensions on a small segment of roadway. Due to the inexpensiveness of the countermeasure, details of the small projects were not well-documented, and information on converted segments is therefore not well-organized. Some of the newly converted segments were identified with the help of district representatives. Around 370 km (230 mi) of 5T highway stretching through 319 control sections was identified from Louisiana highway section database. Each of the 319 sections was reviewed in Google Street View to find any newly reconfigured sections. A total of six sections converted from 4U were identified through these processes.

Google Street View, along with Google Maps, was also used to identify the number and type of driveways and intersections. Changes in the number of driveways and intersections were observed over the years before and after conversion. Only a few driveways, specifically residential, were found obsolete. The number and the type of driveways around the conversion period were used for analysis to avoid confusion. The research team decided to remove one of the sites from the previous study, which is on the Louisiana 1138 highway. This site is in the city of Lake Charles, Louisiana, which was reconfigured in 1999. The imagery around that time was not clear even in Google Maps. Long-term crash data from that site also lacked information such as distance from intersection in the crash database. Fig. 2 presents the locations of selected sites plotted on ArcGIS version 8.2.

The Louisiana Crash 1 database was the source of crash data (LaDOTD 2018). Before and after crash data for up to 7 years was collected. The research team selected the number of years aiming not to interfere with any other influential changes of the roadway other than 5T reconfiguration. Because the EB method was used with SPF of nonintersection crashes, intersection crashes were removed from the database. In Louisiana's crash analysis guidelines, intersection crashes were identified as any crashes that occurred within 45.7 m (150 ft) of the intersection (LaDOTD 2014). Therefore, out of all crashes in a segment, crashes reported as intersection crashes and crashes occurring within 45.7 m of intersections were filtered out to only find the nonintersection crashes.

The characteristics of each site are presented in Table 1. The segments assessed are typically small in length varying from 0.76 to 2.33 km (0.47–1.45 mi). Land use around the sites varies between commercial and residential or is a combination of both. It

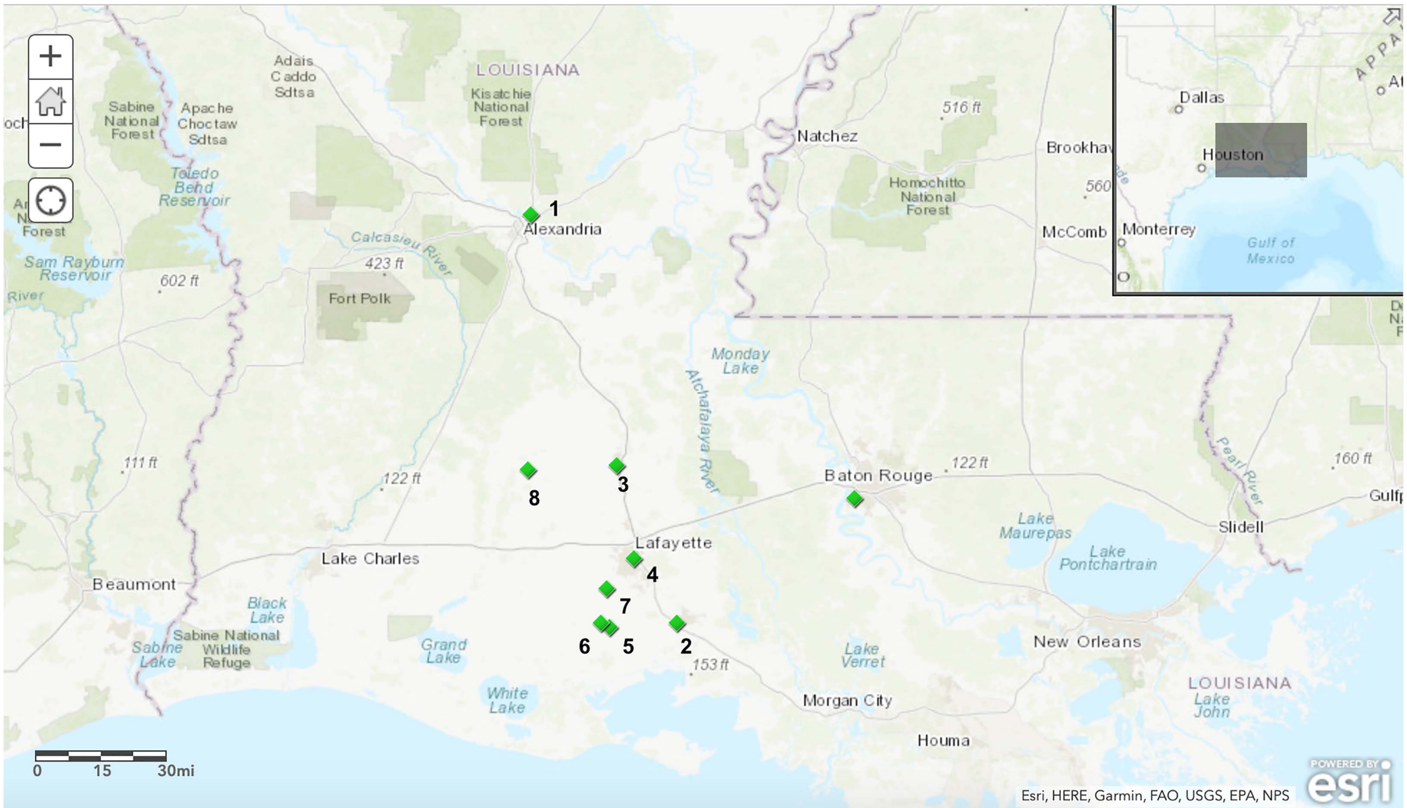

Fig. 2. Site locations. (Esri, HERE, Garmin, FAO, USGS, EPA, NPS, Powered by Esri.)

Table 1. Details of sites

Site characteristic	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7	Site 8	Site 9
Year of conversion	2005	2007	2007	2009	2011	2011	2012	2012	2013
Length [km (mi)]	1.48 (0.92)	1.48 (0.92)	1.61 (1)	1.98 (1.23)	0.76 (0.47)	1.93 (1.2)	1.83 (1.14)	2.33 (1.45)	1.28 (0.8)
Number of years (before)	5	7	6	7	7	7	7	7	7
Number of years (after)	4	7	5	5	5	5	4	4	3
Average AADT (before)	22,262	20,920	15,519	27,304	6,443	15,691	18,748	19,695	17,257
Average AADT (after)	20,856	20,371	19,156	24,880	7,860	17,162	20,098	18,584	24,867
Land use on both sides of roadway	Residential	Commercial	Commercial/ residential	Commercial/ residential	Commercial/ residential	Commercial/ residential	Commercial/ residential	Residential	Commercial/ residential
Speed limit [km/h (mi/h)]	56 (35)	72 (45)	72 (45)	72 (45)	80 (50)	72 (45)	64 (40)	56 (35)	56 (35)
Driveways per km (per mi)	40.5 (65.2)	23 (37)	28.6 (46)	18.7 (30.1)	41 (66)	28 (45)	26.7 (43)	36.9 (59.3)	27.3 (43.9)
Type of driveway									
Major commercial	0	2	0	2	1	1	0	1	0
Minor commercial	60	29	26	12	21	45	35	85	10
Major residential	0	0	0	7	0	0	0	0	2
Minor residential	0	1	21	16	9	7	14	0	23
Minor industrial	0	2	0	0	0	1	0	0	0
Intersection (including both ends of segment)									
Stop control on minor road (T)	8	6	10	7	3	1	1	1	2
Stop control on minor road (cross)	0	0	1	5	2	1	9	14	0
Signalized (three legs)	0	2	1	1	0	0	3	2	0
Signalized (four legs)	1	0	0	1	0	2	1	4	3
Crashes per year									
Before 5T conversion	14	1.9	30.1	11.7	11.7	23.6	32.1	20.7	33.8
After 5T conversion	7	1	28.2	4.8	8	16.7	8.8	9.2	26

Downloaded from ascelibrary.org by Texas A&M University on 08/01/20. Copyright ASCE. For personal use only; all rights reserved.

is interesting that Sites 2, 4, and 8 had a reduction of average AADT after conversion to 5T. Although the focus of the study is to investigate nonintersection crashes, intersection distribution is an important factor to consider with regard to the AADT of the section. The reduction of AADT in Site 5 might be explained by the high density of two-way stop-controlled and signalized intersections. Speed limits of the selected sites vary from 56 to 80 km/h (35–50 mi/h).

EB Method

The EB method has been a popular method for observational before–after studies for more than two decades. The details of the EB method application can be found in many studies (Persaud et al. 2004; Schalkwyk and Washington 2008; Persaud and Lyon 2007; Gross et al. 2013; Hauer 2002). The three major steps in this analysis with unequal before and after years of crash data are described next.

Safety Performance Function

Safety performance function (SPF) estimates the predicted crashes using roadway characteristics such as AADT, length of the roadway segment, roadway width, shoulder width, and number of lanes, among others. Many characteristics associated with the roadway can be used to develop the SPF, but typically AADT along with segment length are considered for observational before–after studies. The LaDOTD developed a SPF for urban four-lane highways to estimate predicted annual total nonintersection crashes (LaDOTD 2016b). The SPF was developed using the annual average of 4U nonintersection crash frequency of 2012–2014.

Because this study uses between 3 and 7 years of crash data for each prediction, a temporal factor was estimated and used for each single prediction of average crash frequency. The temporal factor (γ), sometimes known as time trend factor, also accounts for temporal effects such as variation in weather, demography, and crash reporting (Srinivasan et al. 2011; Persaud et al. 2010). First, statewide length of 4U roadways and the number of statewide nonintersection crashes for each year from 1996 to 2016 were collected from the Crash 1 database. Knowing the particular years of data required for prediction, statewide observed total 4U nonintersection crashes per unit length per year was estimated, and it was divided by the statewide average crashes per unit length per year of 2012–2014 to obtain the temporal factor. Table 2 presents temporal factors for all sites for both before and after years.

Therefore, the final equation of each before or after prediction becomes

$$P = \gamma \times \beta_0 \times L^{\beta_1} \times V^{\beta_2} \times e^{\beta_3 \times V} \tag{1}$$

where γ = temporal factor; P = predicted annual crashes; V = annual average daily traffic (AADT); and $L = 0.621371 \times$ length of roadsegment (km). Parameters used are $\beta_0 = 0.0816$, $\beta_1 = 0.8866$, $\beta_2 = 0.5171$, and $\beta_3 = 0.0000328$.

Table 2. Temporal factors

Site	Temporal factor: Before	After
1	0.90	1.14
2	0.95	1.07
3	0.99	1.11
4	0.73	1.07
5	1.08	1.12
6	1.08	1.12
7	1.13	1.15
8	1.13	1.15
9	1.13	1.20

Estimation of Expected Crashes

The expected annual crashes (E_b) before 5T conversion is estimated from predicted before crashes (P_b) per year and observed average crashes per year in the before period (A_b)

$$E_b = w_1 A_b + w_2 P_b \tag{2}$$

The statistical weighting adjustments w_1 and w_2 from the regression estimate are

$$w_1 = \frac{n_b P_b}{\phi + n_b P_b} \tag{3}$$

and

$$w_2 = \frac{\phi}{\phi + n_b P_b} \tag{4}$$

where n_b = number of years of crash count considered in the before period, where

$$w_1 + w_2 = 1 \tag{5}$$

Considering O_b to indicate the total crashes in the before period, then

$$O_b = n_b A_b \tag{6}$$

Expected annual before period crashes can be estimated from

$$E_b = \frac{\phi + O_b}{\frac{\phi}{P_b} + n_b} \tag{7}$$

where ϕ = inverse overdispersion parameter of the negative binomial distribution that is assumed for the crash counts in estimating the SPF. The LaDOTD estimated the overdispersion parameter as a function of length. The inverse overdispersion parameter becomes

$$\phi = 4.4919 \times L^{\beta_1} \tag{8}$$

where β_1 = regression parameter provided in the DOTD SPF [Eq. (1)].

Expected crashes E_b is then multiplied by a factor C accounting for the change in traffic volumes and other extraneous factors that affect the crash pattern. The factor C is estimated as follows:

$$C = \frac{P_a}{P_b} \tag{9}$$

where P_a = predicted average crashes per year in the after period.

The total number of crashes that could have occurred in the after period had the conversion not been implemented considering the extent of the after period is determined by

$$E_a = C \times n_a \times E_b \tag{10}$$

where n_a = number of years of crash count considered in the after period.

The variance of total crashes in the after period is

$$\mathrm{var}(E_a) = \frac{E_b \times (C \times n_a)^2}{\frac{\phi}{P_b} + n_b} \tag{11}$$

J. Transp. Eng., Part A: Systems, 2020, 146(10): 04020116

Downloaded from ascelibrary.org by Texas A&M University on 08/01/20. Copyright ASCE. For personal use only; all rights reserved.

Estimation of Safety Effectiveness

To estimate the total safety effectiveness, let

$$\pi = \sum E_a \tag{12}$$

$$\lambda = \sum O_a \tag{13}$$

where O_a = observed crash frequency in the after period.

The after-period crash count is assumed to be Poisson distributed, and therefore the variance is equal to the sum of the counts.

Safety can be estimated as follows:

$$\delta = \pi - \lambda \tag{14}$$

An unbiased estimation of safety effectiveness (i.e., CMF) is

$$\theta = \frac{\frac{\lambda}{\pi}}{1 + \frac{\mathrm{var}(\pi)}{\pi^2}} \tag{15}$$

The variance of safety effectiveness is

$$\mathrm{var}(\theta) = \frac{\theta^2 \left[\frac{\mathrm{var}(\lambda)}{\lambda^2} + \frac{\mathrm{var}(\pi)}{\pi^2}\right]}{\left[1 + \frac{\mathrm{var}(\pi)}{\pi^2}\right]^2} \tag{16}$$

Fig. 3 illustrates the EB procedure of estimating the CMF.

Results

EB Results

The EB results are presented in Table 3. The EB estimates of after crashes are always larger than the observed after crashes, demonstrating that a reduction of total nonintersection crashes has been achieved for each site. The individual CMF was as low as 0.210 to up to 0.814, which implies a reduction from 18.6% to as large as 79% of nonintersection crashes in an individual site was achieved. Overall, the CMF was 0.48 (indicates a 52% crash reduction) with a low variance of 0.001. When the 95% confidence interval was estimated, it was seen that all the sites show promising results. Site 6 has the highest CMF (0.99), closest to 1 when the upper boundary of the 95% confidence interval is considered.

This study involves only nonintersection crashes; therefore, it is expected that the majority of the nonintersection crashes (rear-end, left-turn, right-turn, right angle, and head-on) will be generated by the movements from and to driveways. From experience, it was also seen that lane changing with a purpose of entering a driveway results into sideswipe crashes. Therefore, it is imperative to assess the relationship between driveway density and estimated crash reduction. With only nine data points, quadratic regression was found as a better fit over higher-degree polynomial and other nonlinear regressions. Fig. 4 shows a somewhat strong relationship between driveway density and EB-estimated CMF. The square root of the coefficient of determination from the quadratic regression was estimated as 0.52 with no pattern in scatter in the residual plot. The diagram shows that a large crash reduction was achieved at a driveway density ranging from 18 to 31 driveways per kilometer (30–45 driveways per mile).

As previously mentioned, land use around the selected sites is either commercial or residential, or a combination of both. Commercial driveways expectedly generate more traffic than residential driveways. In the Proportion of commercial driveways versus CMF plot (Fig. 5), the square root of the coefficient of determination from the quadratic regression was estimated as 0.76, which indicates a fairly strong relationship. Linear scatter in the residual plot confirms constant error variance and strong support for quadratic regression. The fitted curve in Fig. 5 indicates that the smaller the proportion of commercial driveways, the larger the crash reduction achieved. One study (Williamson and Zhou 2014) explored the safety impact of driveway density on five-lane highways with a left-turn lane and found crash rates for segments with commercial driveways can be 4.6–6.7 times higher compared with crash rates for segments with residential driveways.

Before–After Crash Comparison

Crash rates before and after were also estimated and compared. A comparison of crash rates per million vehicle miles traveled for each project site shows marked improvement, as indicated in Table 4. Crash rates were reduced for each site. A reduction in the crash rate was achieved from 14% to 70%.

Analysis by collision type was also performed (Table 5). Rear-end crashes occurred more frequently compared with other types of crashes prior to 4U to 5T conversion. The largest reduction was

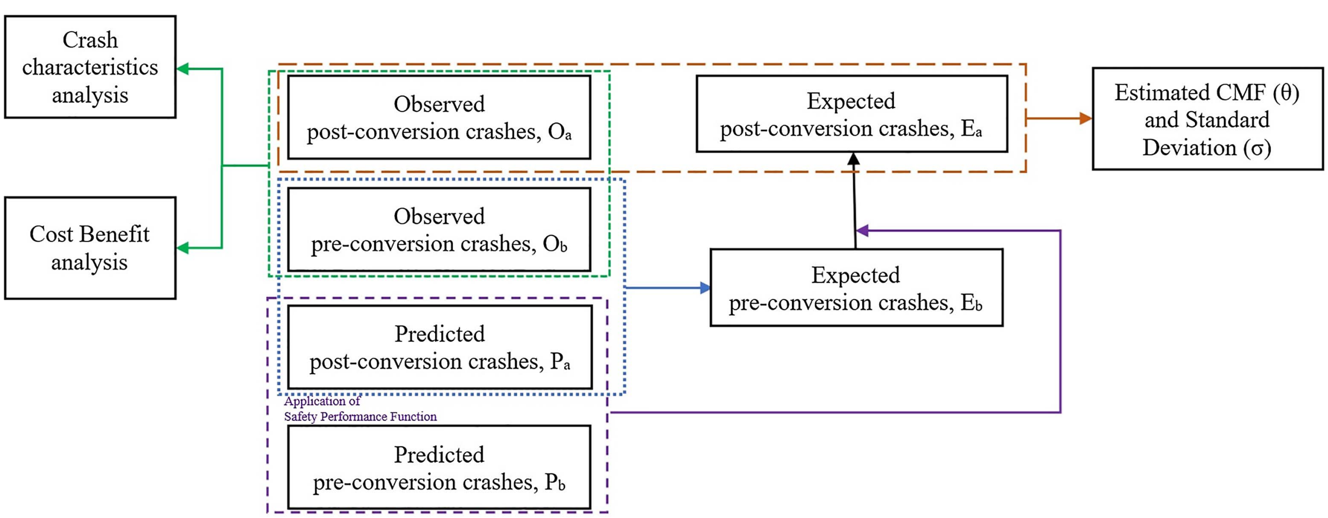

Fig. 3. Crash data analysis procedure including the empirical Bayes CMF estimate.

Downloaded from ascelibrary.org by Texas A&M University on 08/01/20. Copyright ASCE. For personal use only; all rights reserved.

Table 3. EB results

Site	After period count, O_a	EB estimate, E_a	$\mathrm{var}(E_a)$	CMF/safety effectiveness, θ	$\mathrm{var}(\theta)$	95% confidence interval
1	104	156.0	122.5	0.663	0.006	(0.51, 0.82)
2	49	108.8	218.3	0.442	0.007	(0.27, 0.61)
3	46	145.7	222.8	0.312	0.003	(0.20, 0.42)
4	44	208.4	260.3	0.210	0.001	(0.14, 0.28)
5	5	12.5	31.1	0.334	0.031	(0, 0.68)
6	141	172.4	134.2	0.814	0.008	(0.64, 0.99)
7	19	53.5	92.5	0.344	0.009	(0.15, 0.53)
8	32	46.9	78.1	0.659	0.027	(0.34, 0.98)
9	50	115.9	115.4	0.428	0.005	(0.29, 0.57)
Total	490	1,020.0	1,275.2	0.480	0.001	(0.43, 0.53)

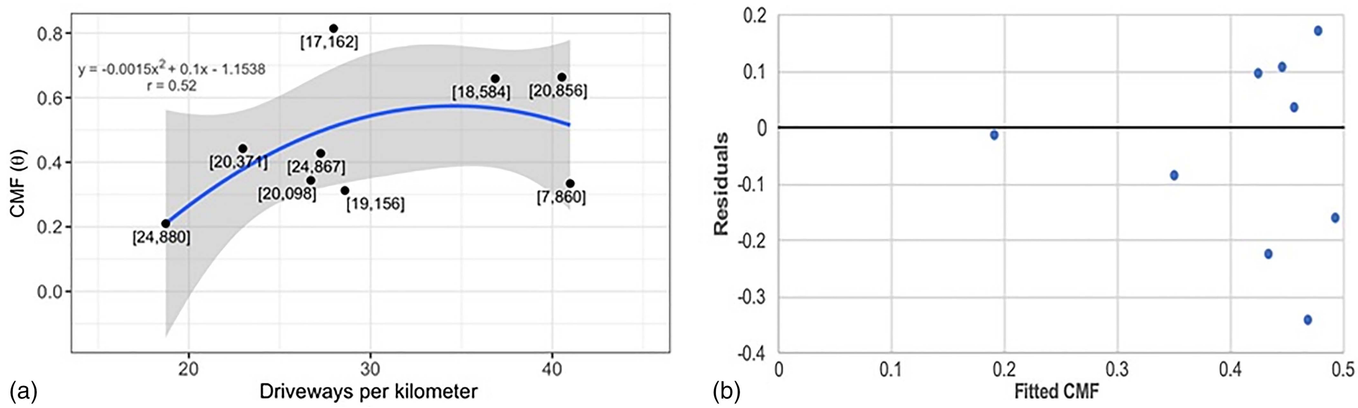

Fig. 4. (a) Driveway density versus CMF plot at different AADT with 95% confidence limits; and (b) residual plot.

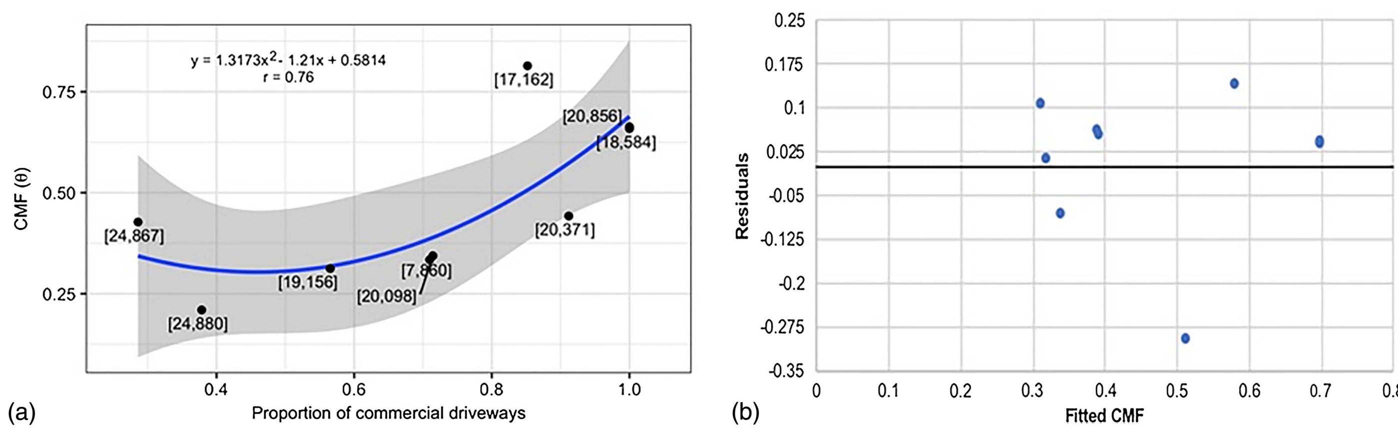

Fig. 5. (a) Proportion of commercial driveways versus CMF plot at different AADT with 95% confidence limits; and (b) residual plot.

Table 4. Observed before–after crash rate

Site	Before crash rate[a]	After crash rate[a]	Change (%)
1	2.81	2.31	−18
2	1.24	0.64	−49
3	2.27	0.82	−64
4	1.63	0.49	−70
5	1.04	0.46	−56
6	2.73	2.33	−14
7	0.93	0.35	−62
8	0.70	0.51	−28
9	2.91	1.43	−51

[a]Per million vehicle kilometers.

achieved in rear-end crashes, a 60% overall reduction. All the sites experienced rear-end crash reduction. Angle crashes (left-turn, right-turn, and right-angle crash) were the second most frequent type of crashes. All sites except Sites 2 and 9 had a reduction of angle crashes per year. An extensive review of the crash reports demonstrates that most of the after-year angle crashes still occurred when crossing more lanes for entering and exiting driveways. The most noticeable increase was in same-direction sideswipe crashes occurring mainly due to poor lane-changing decisions. However, this increase might also be attributable to the reduction of lane width because the sites that experienced an increase in same-direction sideswipe crashes had at least one through-lane width reduced to 2.74–2.9 m (9–9.5 ft) after reconfiguration to 5T.

J. Transp. Eng., Part A: Systems, 2020, 146(10): 04020116

Downloaded from ascelibrary.org by Texas A&M University on 08/01/20. Copyright ASCE. For personal use only; all rights reserved.

Table 5. Change in crash type

Site	Crash type	Before crashes per year	After crashes per year	Change (%)
1	Rear-end	0.86	0.4	−53
	Left-turn	0.43	0	−100
	Right-turn	0	0	0
	Head-on	0.14	0	−100
	Same-direction sideswipe	0	0.4	Increase
	Opposite-direction sideswipe	0	0	0
2	Rear-end	5.29	2.75	−48
	Left-turn	0.86	0.5	−42
	Right-turn	0.43	0.25	−42
	Head-on	0	0	0
	Same-direction sideswipe	2	2	0
	Opposite-direction sideswipe	0.14	0.25	75
3	Rear-end	8.71	4.67	−46
	Left-turn	2.86	1.67	−42
	Right-turn	0.29	1	250
	Head-on	0.14	0.33	133
	Same-direction sideswipe	3	4	33
	Opposite-direction sideswipe	0.29	0	−100
4	Rear-end	21.29	3	−86
	Left-turn	0.71	0.4	−44
	Right-turn	0	0.2	Increase
	Head-on	0.14	0	−100
	Same-direction sideswipe	3.43	1.4	−59
	Opposite-direction sideswipe	1.14	0.2	−83
5	Rear-end	10.83	3.2	−70
	Left-turn	0.33	0.6	80
	Right-turn	0.33	0.8	140
	Head-on	0	0	0
	Same-direction sideswipe	2.33	1.6	−31
	Opposite-direction sideswipe	0.17	0	−100
6	Rear-end	16.6	7.75	−53
	Left-turn	1	4.75	375
	Right-turn	1.2	1	−17
	Head-on	0	0.5	Increase
	Same-direction sideswipe	3.2	5.25	64
	Opposite-direction sideswipe	0.2	0.25	25
7	Rear-end	6.71	1	−85
	Left-turn	0	0.25	Increase
	Right-turn	0.14	0.25	75
	Head-on	0.14	0	−100
	Same-direction sideswipe	1.57	1.25	−20
	Opposite-direction sideswipe	0.14	0.5	250
8	Rear-end	18.57	11.4	−39
	Left-turn	0.86	1.6	87
	Right-turn	0.29	0.4	40
	Head-on	0.71	0.2	−72
	Same-direction sideswipe	2.86	6.4	124
	Opposite-direction sideswipe	0.57	0.6	5
9	Rear-end	3.57	2.57	−28
	Left-turn	1.71	0.57	−67
	Right-turn	0.43	0.29	−33
	Head-on	0	0.14	Increase
	Same-direction sideswipe	1	1.86	86
	Opposite-direction sideswipe	0	0	0

Opposite-direction crashes (head-on and opposite-direction sideswipe) are the least frequent in number, although increased somewhat in 3 sites. In a few cases, opposite direction sideswipe crashes happened with vehicles in the left-turn lane. Again, narrow lane width can be associated with this particular type of crash because the left-turn lane width is typically 3.05 m (10 ft). However, these conclusions cannot be made with certainty based on only a limited number of incidents.

Table 6. Benefit cost analysis

Injury type	Crash reduction (crashes per year)	Crash cost	Benefit
Fatal (K)	−0.2	$1,710,561	−$342,112
Severe (A)	0.3	$489,446	$146,834
Moderate (B)	3.7	$173,578	$640,585
Complaint (C)	18.2	$58,636	$1,066,756
None (O)	48	$24,982	$1,199,374
Estimated total benefit per year			$2,711,437
Restriping cost of 3 years per km			$7,115
Total cost per year			$34,831
Benefit cost ratio			78:1

Crashes by the time of the day were also analyzed. Crashes per year reduced for all four quarters of the day. A 47% reduction of crashes was observed during both 12:00–6:00 p.m. and 6:00 p.m.–12:00 a.m. periods. Crashes per year were also reduced for both dry and wet pavement surface conditions by 35% and 59%, respectively.

Benefit Cost Ratio

The benefit was estimated according to the latest crash cost of different injury types as classified by the DOTD using the KABCO injury scale where injuries were K (killed/fatal), A (severe), B (moderate), C (there was a complaint of injury, but no injury was visible), or O (no injury, but property damage only). Due to unequal before and after years' data, the crash reduction per year for each injury type was estimated for each site. Each injury type crash reduction per year was summed up for all sites. Then, the benefit of each injury type per year was obtained by multiplying the crash cost with that total injury type crash reduction of all sites per year. Summing up the benefits of all injury types provides a total benefit per year. Only one fatal crash occurred in a 4U to 5T conversion segment in the after years and had nothing to do with the project. Still, that fatal crash cost was calculated as a loss in the benefit estimation.

According to a previous study in Louisiana (Sun et al. 2012), the overestimated cost of restriping including both materials and labor is $7,115 per km ($11,450 per mi). Restriping was assumed to last about 3 years. The total cost of restriping was calculated dividing $7,115 by 3 and multiplying the total length of the project sites of 14.69 km (9.13 mi). Finally, the safety benefit-cost ratio was estimated as 78:1 by dividing the total benefit per year by the total cost per year. The benefit-cost estimation is presented in Table 6.

Conclusions

This study investigated the safety performance of 4U to 5T conversion in Louisiana by estimating a CMF. The EB method was used with a DOTD-developed SPF and estimated temporal factors to avoid any potential regression-to-the-mean bias. Using up to 7 years of crash data, the nine conversion sites with different land uses were evaluated. The relationships of CMF with driveway density and proportion of commercial driveway density were identified and illustrated. The quadratic regression line of CMF shows that 4U to 5T conversion performs very well at a driveway density ranging from 18 to 31 driveways per kilometer (30–50 driveways per mile). However, with only nine samples, this estimation is not conclusive and might not be applicable to every 4U to 5T conversion.

J. Transp. Eng., Part A: Systems, 2020, 146(10): 04020116

Downloaded from ascelibrary.org by Texas A&M University on 08/01/20. Copyright ASCE. For personal use only; all rights reserved.

The overall estimated CMF for all nine sites was 0.48 with a small variance, which means five-lane conversions are expected to achieve a 52% total crash reduction. Estimated CMF results also show that this lane reconfiguration is effective for adjacent land use with commercial or residential establishments or a combination of both. Comparison of the before and after crash rate also represents a positive effect, with up to a 70% crash rate reduction achieved.

Investigation of crash type demonstrates a noteworthy reduction in almost all crash types. In undivided multilane highways, rear-ending was presumably the most prevalent crash type. Rear-end crashes were substantially reduced after conversion to 5T. Some sites showed small increases in angle crashes and same-direction sideswipe crashes, which was not unexpected.

The previous study (Sun and Das 2013) also estimated the CMFs using the Improved Prediction method by adjusting traffic volume. Estimated CMFs for Sites 7, 8, and 9 were 0.45, 0.43, and 0.47, very consistent CMFs despite the difference in driveway density. Because that method with traffic adjustment also included intersection crashes with only 3 years of data, comparison with nonintersection CMFs in this study estimated with the EB method (0.34, 0.66, and 0.43) is impractical. However, both studies yielded a positive impact of the conversion.

This lane conversion proves to be a very effective low-cost crash countermeasure for urban and suburban roadways with low to moderate AADT. The 4U to 5T conversion might be an effective option for crash reduction under a budgetary constraint. The very high safety benefit-cost ratio, 78:1, indicates strong support to use this countermeasure on four-lane undivided roadways. However, implementation of this conversion requires additional evaluation for feasibility.

This study provides a broader look to the conversion of four-lane undivided highway to five-lane undivided highway with a left-turn lane. It is expected that this study will set a pedestal for future studies on this topic. However, the scope of the study can be expanded. Primarily by developing the SPFs of injury crashes and rear-end crashes, the EB estimated CMFs for those crashes can be explored. Only 9 out of 10 sites were available for analysis in Louisiana. More sites in other states can obviously strengthen the result of the overall CMF. With more studies, it can be evaluated, along with the much more popular 3T conversion, whether this 5T conversion of 4U highways can be an effective crash countermeasure alternative.

Future studies can be conducted on the EB estimate of safety for different injury crash types or crashes by manner of collision. It also remains to be comprehensively investigated whether lane-width reduction can be an issue leading to an increase of sideswipe crashes. The safety of the intersections within the segment can also be evaluated because it is also expected to increase.

Data Availability Statement

All data, models, or code generated or used during the study will be available from the corresponding author by request.

Acknowledgments

This study was sponsored by the Louisiana Transportation Research Center (LTRC). It was a part of the project "Investigating Safety Impact of Centerline Rumble Strips, Lane Conversion, Roundabout and J-Turn Features on Louisiana Highways." The authors would like to acknowledge the support from all local district offices of the Louisiana DOTD. This study was presented in the 96th TRB annual meeting, and the comments by the discussants are greatly appreciated. The authors also would like to thank Jacob Moreau for his assistance in data processing.

References

AASHTO. 2010. *Highway safety manual*. 1st ed. Washington, DC: AASHTO.

AASHTO. 2018. *Policy on geometric design of highways and streets*. 7th ed. Washington, DC: AASHTO.

CMF Clearinghouse. 2018. "Crash modification factors clearinghouse." Accessed February 2, 2017. http://www.cmfclearinghouse.org/index.cfm.

FHWA (Federal Highway Administration). 2017. *Road diet case studies*. FHWA-SA-15-052. Washington, DC: FHWA.

Gross, F., C. Lyon, B. Persaud, and R. Srinivasan. 2013. "Safety effectiveness of converting signalized intersections to roundabouts." *Accid. Anal. Prev.* 50 (Jan): 234–241. https://doi.org/10.1016/j.aap.2012.04.012.

Hauer, E. 2002. *Observational before-after studies in road safety: Estimating the effects of highway and traffic engineering measures on road safety.* Oxford, UK: Pergamon.

Huang, H., J. Stewart, and C. Zegeer. 2002. "Evaluation of lane reduction 'road diet' measures on crashes and injuries." *Transp. Res. Rec.* 1784 (1): 80–90. https://doi.org/10.3141/1784-11.

Knapp, K., B. Chandler, J. Atkinson, T. Welch, H. Rigdon, R. Retting, S. Meekins, E. Widstrand, and R. J. Porter. 2014. "*Road diet informational guide*." Rep. No. FHWA-SA-14-028. Washington, DC: FHWA.

LaDOTD (Louisiana Department of Transportation and Development). 2009. "Design guidelines." Accessed June 5, 2015. http://wwwsp.dotd.la.gov/Inside_LaDOTD/Divisions/Engineering/Road_Design/Memoranda/English_Design_Guidelines.pdf.

LaDOTD (Louisiana Department of Transportation and Development). 2014. "Guidelines for crash data analysis." Accessed July 30, 2015. http://wwwsp.dotd.la.gov/Inside_LaDOTD/Divisions/Multimodal/Highway_Safety/Misc%20Documents/Guidelines%20for%20Conducting%20a%20Crash%20Data%20Analysis.pdf.

LaDOTD (Louisiana Department of Transportation and Development). 2015. *Highway section database*. Baton Rouge, LA: LaDOTD.

LaDOTD (Louisiana Department of Transportation and Development). 2016a. "Guidelines for conducting a crash data analysis using the number-rate method and overrepresented determination." Accessed January 2, 2017. http://wwwsp.dotd.la.gov/Inside_LaDOTD/Divisions/Multimodal/Highway_Safety/Misc%20Documents/Guidelines%20for%20Crash%20Data%20Analysis%20using%20the%20Number-Rate%20Method%20and%20Overrepresentation%20-%20Jan%202016.pdf.

LaDOTD (Louisiana Department of Transportation and Development). 2016b. "Guidelines for conducting a crash data analysis using safety performance functions and pattern recognition analysis." Accessed January 2, 2017. http://wwwsp.dotd.la.gov/Inside_LaDOTD/Divisions/Multimodal/Highway_Safety/Misc%20Documents/Guidelines%20for%20Crash%20Data%20Analysis%20using%20SPFs%20and%20Pattern%20Recognition%20Analysis%20-%20Jan%202016.pdf.

LaDOTD (Louisiana Department of Transportation and Development). 2018. *Crash 1 database*. Baton Rouge, LA: LaDOTD.

ODOT (Oklahoma DOT). 2007. "US-81 corridor study: 4-lane vs. 5-lane comparison/recommendation." Accessed January 8, 2018. http://www.okladot.state.ok.us/p-r-div/us81corridor/appendh.pdf.

Persaud, B., B. Lan, C. Lyon, and R. Bhim. 2010. "Comparison of empirical Bayes and full Bayes approaches for before–after road safety evaluations." *Accid. Anal. Preven.* 42 (1): 38–43. https://doi.org/10.1016/j.aap.2009.06.028.

Persaud, B., and C. Lyon. 2007. "Empirical Bayes before–after safety studies: Lessons learned from two decades of experience and future directions." *Accid. Anal. Preven.* 39 (3): 546–555. https://doi.org/10.1016/j.aap.2006.09.009.

Persaud, B. N., R. A. Retting, and C. A. Lyon. 2004. "Crash reduction following installation of centerline rumble strips on rural two-lane

Downloaded from ascelibrary.org by Texas A&M University on 08/01/20. Copyright ASCE. For personal use only; all rights reserved.

roads" *Accid. Anal. Preven.* 36 (6): 1073–1079. https://doi.org/10.1016/j.aap.2004.03.002.

Schalkwyk, I. V., and S. P. Washington. 2008. *Cost effective safety improvements for two-lane rural roads in Washington State*. Rep. No. WA-RD 695.1. Olympia, WA: Washington State Dept. of Transportation.

Srinivasan, R. 2011. *Evaluation of safety strategies at signalized intersections*. Washington, DC: Transportation Research Board.

Sun, X., and S. Das. 2013. *Developing Louisiana crash reduction factors*. Rep. No. FHWA/LA. 12/506. Washington, DC: Federal Highway Administration.

Sun, X., S. Das, N. Fruge, R. L. Bertinot, and D. Magri. 2012. "Four-lane to five-lane urban roadway conversions for safety." *J. Transp. Saf. Secur.* 5 (2): 106–117. https://doi.org/10.1080/19439962.2012.711439.

Welch, T. M. 1999. "The conversion of four lane undivided urban roadways to three lane facilities." In *Proc., TRB/ITE Urban Street Symp.*, 28–30. Washington, DC: Transportation Research Board, National Research Council.

Williamson, F., and H. Zhou. 2014. "A study of safety impacts of different types of driveways and their density." In *Proc., 9th Int. Conf. on Traffic & Transportation Studies*, 576–583. Beijing: Social and Behavioral Sciences.

Downloaded from ascelibrary.org by Texas A&M University on 08/01/20. Copyright ASCE. For personal use only; all rights reserved.