Evaluation of the Safety Effectiveness of the Conversion of Two-Lane Roadways to Four-Lane Divided Roadways

Bayesian Versus Empirical Bayes

Mohamed M. Ahmed, Mohamed Abdel-Aty, and Juneyoung Park

This paper uses various observational before–after analyses to evaluate the safety effectiveness of widening urban and rural two-lane to four-lane divided roadways. The methods range from simple (naive) before–after, before–after with comparison group, empirical Bayes (EB), and Bayesian approach. The EB method requires safety performance functions (SPFs) to be calibrated; the simple SPF based on annual average daily traffic (AADT) is used widely. In this paper, two sets of negative binomial models are calibrated: the full SPF model, which uses various explanatory covariates, and the simple SPF, which uses AADT only. The preliminary results from the calibrated models indicate that the SPF is pivotal in the EB method; the more accurate the models, the more pragmatic the evaluation of the safety effectiveness of a treatment. The proposed method of using the full SPF in the EB method is recommended over the conventional EB observational before–after. To obtain more reliable estimates, the Bayesian before–after approach is performed. The Bayesian bivariate Poisson–lognormal approach provides comparable results and may have several advantages over the EB technique. The results from this paper indicate that the conversion from two-lane roadways to four-lane divided roadways results in a notable reduction in fatal and injury crashes of more than 63% on urban roadways and 45% on rural roadways. Conversion to a four-lane divided roadway produces a higher reduction in total and property damage only crashes in urban areas than it did in rural areas. In addition, the safety effects of the conversion appear to be more effective on roadway segments in urban areas with a high AADT value.

Evaluating the safety effectiveness of how crash frequency or severity has changed as a result of a specific improvement or a combination of improvements is a vital step in roadway safety studies. Improvements and countermeasures are motivated mainly by any or all of the following: planning, traffic operation, and safety reasons. One major improvement that is considered to be planning driven is widening roadways. Adding a lane or multiple lanes is warranted mostly when more traffic demand is projected (commonly, a 20-year planning period). The relationship between roadway capacity and its number of lanes is plausibly well defined in the *Highway Capacity Manual* (*1*). While the manual provides the level of service as a measure to determine the operational effectiveness of elements of the transportation infrastructure with an implicit indication of the corresponding safe driving conditions, the explicit effect on safety of the number of lanes and the cross-section elements is not fully understood.

There are multiple factors affecting safety on roadway segments, including driver behavior, traffic and geometric characteristics, weather conditions, and interrelationships between these factors. Although safety performance functions are commonly used to quantify the relationship between traffic and roadway characteristics and safety on urban and rural roadways, the safety effects of adding lanes and changing the cross-section configuration of roadways are not quite clear. The decision of selecting a cross section of a roadway (i.e., the number of lanes, presence and width of a median, lane width, and shoulder width) can greatly affect safety, cost, and level of service. The number of lanes and the cross-section configuration are considered to be among the most important factors, yet the least researched, in the effect on safety in the context of a before–after study.

The commission meeting on the Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users in 2007 acknowledged that it is not possible to make firm statements about the safety effects of adding lanes to facilities where right-of-way is increased (*2*). The commission indicated that the lack of sound before–after studies is the main reason behind this mystification.

Kononov et al. identified a lack of understanding of the effect of the number of lanes on the traffic safety of freeways (*3*). They conducted a cross-sectional study to compare the slopes of safety performance functions (SPFs) of different numbers of lanes on freeways in different states. It was concluded that adding lanes on urban freeways resulted initially in safety improvement, but that it diminished as congestion increased.

Previous studies indicated that roadways with raised medians are safer and operate better than any other access management cross-section configuration. Multilane divided roadways were found to be safer than two-way, two-lane roadways in North Carolina, indicated by a 93% reduction in fatal crashes and a 71% drop in property damage only (PDO) crashes (*4*). In urban areas, results from previous studies indicated that raised median roadways are 25% to 30% safer than undivided roadways (*5*).

Noland and Oh depicted conflicting findings that geometric improvements, including widening roadways, adding lanes, and reducing the curvature, have no safety benefits (*6*). Abdel-Aty and Radwan found

M. M. Ahmed, Department of Civil and Architectural Engineering, University of Wyoming, 1000 East University Avenue, Laramie, WY 82071. M. Abdel-Aty and J. Park, Department of Civil, Environmental, and Construction Engineering, University of Central Florida, 4000 Central Florida Boulevard, Orlando, FL 32816-2450. Corresponding author: M. M. Ahmed, mahmed@uwyo.edu.

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that an increase in the number of lanes leads to crash rate increases on urban roadway sections (*7*).

Council and Stewart used cross-sectional analysis to evaluate the safety of converting two-lane roads to four-lane divided roads in four states, California, Michigan, North Carolina, and Washington (*8*). The results indicated a 40% to 60% reduction in total crashes. Their study found that the reduction in crashes appeared to decrease very slightly as average annual daily traffic (AADT) increased for California and North Carolina, while it increased with increases in AADT for Minnesota and Washington.

The results from existing cross-sectional analyses, however, are not as strong as results from observational before–after studies with a sufficient sample of treated sites where two-lane roadways were upgraded to four-lane divided roadways. To the authors' knowledge, there are no studies that have adopted observational before–after analysis of the conversion of two-lane to four-lane roadways because of the lack of treated sites. While the empirical Bayes (EB) approach has been the most common and rigorous approach to perform observational before–after evaluations in the past two decades, with the advancement in statistical modeling techniques and computing capabilities, other approaches using the Bayesian method are gaining momentum (*9–13*). In this paper, various observational before–after studies have been conducted to evaluate the safety effectiveness of adding a lane and adding a raised median on urban and rural two-lane roadways. The following sections illustrate procedures for preparing the data and statistical methods and provide results and discussion and the conclusion.

DATA DESCRIPTION AND PREPARATION

Observational before–after studies are the most common and accepted approach for evaluating safety effectiveness. The evaluation methods are very data intensive; the evaluation is more complex than comparing before and after crash data at treatment sites because consideration is also given to changes in traffic and various other factors. Three sets of data are used in this study: (*a*) information from the sites where the treatment (conversion from two-lane roadways to four-lane divided roadways) was applied, (*b*) information from a comparison group, and (*c*) information from reference sites to develop the SPFs. The information on all widening projects on urban and rural two-lane roadways that were initiated and completed between 2005 and 2009 in the state of Florida were collected first. The data were collected from the Florida Department of Transportation's financial project search website available on the agency's intranet (*14*). For each of the 84 urban and rural roadway segments that were identified, the collected information included start date, end date, roadway ID, beginning milepost, ending milepost, and additional traffic and roadway characteristics data. Google Earth and Video Logs were also used to verify the treated sites and their accurate start and end dates. Table 1 presents descriptive statistics of the conversion of two-lane roadways to four-lane divided roadways in urban and rural areas. The upgraded two-lane roadways consisted of 41 urban and 43 rural segments. The total length of the identified treated sites was about 41 mi.

The crash data for the aforementioned treated sites during the before (3 years before construction start date) and after periods

TABLE 1 Summary of Data on Conversion of Two-Lane to Four-Lane Divided Roadways

Roadway Type	Number of Segments	Average Segment Length (mi)	Total Length (mi)	Average Value of AADT	Total Crash (F+I Crash) (PDO Crash)			
					Mean	SD	Min.	Max.
Treated Sites								
U2-U4[a] Before period	41	0.209	8.578	18,544	1.68 (0.84) (0.84)	2.69 (1.40) (1.75)	0 (0) (0)	9 (6) (7)
After period	41	0.209	8.578	21,030	0.72 (0.39) (0.33)	1.10 (0.54) (0.104)	0 (0) (0)	6 (2) (6)
R2-R4[b] Before period	43	0.763	32.808	9,539	3.00 (1.91) (1.09)	4.51 (3.29) (2.20)	0 (0) (0)	22 (18) (10)
After period	43	0.763	32.808	10,896	2.63 (1.67) (0.97)	3.60 (2.54) (1.69)	0 (0) (0)	14 (10) (8)
Comparison Groups								
U2-U4[a] Before period	381	0.178	67.814	16,376	1.19 (0.72) (0.47)	2.95 (1.23) (1.04)	0 (0) (0)	27 (17) (13)
After period	381	0.178	67.814	16,698	1.52 (1.06) (0.36)	2.95 (1.44) (1.12)	0 (0) (0)	23 (11) (13)
R2-R4[b] Before period	370	0.623	230.331	9,805	1.83 (1.22) (0.61)	5.51 (3.70) (2.57)	0 (0) (0)	55 (35) (26)
After period	370	0.623	230.331	10,355	2.01 (1.24) (0.77)	6.61 (3.89) (2.90)	0 (0) (0)	69 (48) (21)

NOTE: F+I = fatal and injury; SD = standard deviation; min. = minimum; max. = maximum.
[a]U2-U4 = urban two-lane–urban four-lane.
[b]R2-R4 = rural two-lane–rural four-lane.

(2 years and 6 months after the construction end date) were collected from the crash analysis reporting system, and the geometric characteristics and traffic volumes (AADT) were gathered from the roadway characteristics inventory database. The crash data were segregated into three types: total number of crashes, severe crashes [fatal and injury (F+I)], and PDO crashes. There was a general trend of crash reduction after the conversion of two-lane roads to four-lane divided roads in all roadway segments; the average crash per mile per year was 1.5 and 0.81 for the treated rural and urban two-lane roadways in the before period, respectively. In the after period, the average crash per mile per year was 1.08 and 0.78 for rural and urban roadway segments, respectively.

The next step in data collection was to collect information on a comparison group of sites that remained untreated. The before–after with comparison group method required information of sites similar to the treated sites in the trend of crash history; thus traffic, geometric, and geographic characteristics were also collected. The size of a comparison group should be at least five times larger than the treatment sites as suggested by Pendleton (*15*). Selecting a matching comparison group with a similar yearly trend of crash frequencies in the before period could be a daunting task. In this study a matching of comparison group to treatment sites of at least 5 to 1 was conducted with an identical length of 3 years of the before and 3 years of the after periods. A total length of 298 mi of two-lane roadways in Florida were identified to satisfy criteria indicated in Table 1. The crash data and geometric and traffic characteristics for these roadway segments were obtained from the crash analysis reporting system and roadway characteristics inventory databases.

As discussed earlier, another objective of this study was to compare the commonly used observational before–after approaches (i.e., naive, comparison group, and EB) with the Bayesian method. The identified comparison group of sites was used in the Bayesian estimation. A main difference between the EB method and the Bayesian approach was the data requirements. The EB method required information from a reference group of sites, while full Bayesian (FB) required a smaller comparison group of sites. A reference group of sites was needed to provide prior information with sample mean and variance for the expected crashes similar to those under evaluation and to calibrate SPFs that related crash frequency to some explanatory variables. Comparison group data are commonly chosen with traffic and environmental conditions similar to the treated sites to correct for time trend effects (e.g., confounding factors of crash history and maturation). The reference sites are different from the comparison group; the reference sites are broader than the comparison group with more variation in AADT, roadway characteristics, and crash history to correct for the regression-to-the-mean artifact. The comparison group corrects for other important effects, such as unrelated maturation and long-term collision trends.

The Bayesian approach integrates the EB two steps into one, and hence Bayesian uses information from a comparison group of sites and the before information from the treated sites to estimate the long-term expected crash frequency. Roadway geometry data were collected from roadway characteristics inventory and matched to crash data collected from the crash analysis reporting system database. Information about the comparison group is listed in Table 1. More reference sites information with the corresponding roadway characteristics and traffic data were collected to calibrate reliable SPFs for the EB method. A total of 1,291 and 1,301 urban and rural, reference two-lane roadway segments, respectively, were identified with a similar yearly traffic trend, physical characteristics, and land use in the whole state of Florida.

METHOD

Crash modification factors express the safety consequences of some treatment or intervention that has been implemented on a roadway facility. As mentioned earlier, one of the main methods to examine the effect of highway and traffic engineering measures on safety is the observational study. Observational studies can be categorized into two main groups: (*a*) before–after and (*b*) cross sectional.

The observational before–after study is more advantageous than the cross-sectional observational study since it can capture the safety implications of a certain improvement or operational change in cases in which many of the attributes (e.g., geometry and other site characteristics) of a study facility remain unchanged. The cross-sectional approach cannot be trusted to represent causal relationships. For example, evaluation of the safety effect associated with installing a raised median falls under the observational before–after study category. In contrast, in the cross-section observational study, the safety implications of one group of entities with some common feature (e.g., four-lane divided roadway segments) are compared with the safety of a different group of entities without that feature (e.g., four-lane undivided roadway segments). Data availability can determine which method to adopt.

Naive and Before–After with Comparison Group

The naive before–after approach is the simplest approach. Crash counts in the before period are used to predict the expected crash rate and, consequently, the expected crashes had the treatment not been implemented. This basic naive approach assumes that there was no change from the before to the after period that affected the safety of the entity under scrutiny; hence, this approach is unable to account for the passage of time and its effect on other factors such as exposure, maturation, trend, and regression-to-the-mean bias.

The before–after with comparison group study can be adopted to account for the influence of a variety of external causal factors that change with time. A comparison group is a group of control sites that remained untreated and that are similar to the treated sites in trend of crash history, traffic, and geometric and geographic characteristics. The crash data of the comparison group are used to estimate the crashes that would have occurred at the treated entities in the after period had treatment not been applied. This method can provide more accurate estimates of the safety effect than a naive before–after study, particularly if the similarity between treated and comparison sites is high. The before–after with comparison group method is based on two main assumptions: (*a*) the factors that affect safety have changed in the same manner from the before period to the after period in treatment and comparison groups and (*b*) these changes in the various factors affect the safety of the treatment and comparison groups in the same way (*16*). The detailed before–after with comparison group method can be found in Hauer (*16*).

Before–After with EB Method

In the before–after with the EB method, the expected crash frequencies at the treatment sites in the after period had the countermeasures not been implemented are estimated more precisely with data from the crash history of a treated site, as well as the information of what is known about the safety of reference sites with a similar yearly traffic trend, physical characteristics, and land use.

The method is based on three fundamental assumptions: (*a*) the number of crashes at any site follows a Poisson distribution, (*b*) the means for a population of systems can be approximated by a gamma distribution, and (*c*) changes from year to year from sundry factors are similar for all reference sites (*16*).

One main advantage of the before–after study with EB is that it accurately accounts for changes in crash frequencies in the before and in the after periods at the treatment sites that may be the result of regression-to-the-mean bias. It is also a better approach than the comparison group for accounting for the influences of traffic volumes and time trends on safety. See Hauer for further details about the before–after study with EB (*16*).

Safety Performance Functions

"Level of service of safety" was defined by Kononov and Allery as the way the roadway segment is performing in regard to its expected crash frequency and severity at a specific level of AADT (*17*). Unfortunately, the estimated expected crashes can vary extensively over the chosen function and covariates, and hence SPFs play a key role in determining the actual safety effect of roadway improvements.

Data from the untreated reference group are used to first estimate an SPF that relates crash frequency of the sites to their traffic and geometrical characteristics. Generally, an SPF is a crash prediction model, which relates the frequency of crashes to traffic (e.g., average daily traffic) and the roadway characteristics (e.g., number of lanes, width of lanes, and width of shoulder). There are two main types of SPFs in the literature: (*a*) "full" SPFs and (*b*) "simple" SPFs. A full SPF is a mathematical relationship that relates traffic parameters and geometric parameters as explanatory variables, whereas a simple SPF includes AADT as the sole explanatory variable in predicting crash frequency on a roadway entity. In this study, simple and full SPFs are developed for different roadway entities. Moreover, different SPFs are estimated separately by land use (rural and urban) for total crashes and F+I crashes. The negative binomial (NB) (known also as Poisson–gamma) model has been used widely in crash analysis. The NB model is favored because crash data have a gamma-distributed mean for a population of systems, allowing the variance of the crash data to be more than their mean (*18*).

NB regression models were developed and used to estimate the number of crashes at the treated sites. Two sets of SPFs were estimated with the use of the NB: simple SPF and full SPF. With the PROC GENMOD procedure in SAS, NB models were fitted for the frequency of reference group crashes with the explanatory variables attempted: log(AADT), length of the segment, width of shoulder, width of lane, and speed limit (*19*). Simple and full SPFs were fitted for the total number of crashes and for F+I crashes.

Tables 2 and 3 show the results for the simple and full SPF models, respectively, for total crashes and injury (F+I) crashes on urban

TABLE 2 Simple Florida-Specific SPFs Calibrated to Florida Data for Urban and Rural Two-Way, Two-Lane Segments: Total and F+I Crashes

	Calibrated Florida-Specific Simple SPFs-MLE Negative Binomial					
	Intercept		log(AADT)			
Severity	Estimate	*P*-Value	Estimate	*P*-Value	Dispersion (*k*)	Deviance
Urban						
Total	−5.0195	<.0001	0.7864	<.0001	0.9157	1,378.51
PDO	−6.0647	<.0001	0.7952	<.0001	0.8415	1,324.72
F+I	−5.9485	<.0001	0.7621	<.0001	0.7133	1,318.92
Rural						
Total	−8.1513	<.0001	0.9388	<.0001	0.631	1,175.28
PDO	−7.6386	<.0001	1.0867	<.0001	0.8078	1,198.84
F+I	−8.264	<.0001	0.805	<.0001	0.678	1,294.47

NOTE: MLE = maximum likelihood estimate.

TABLE 3 Full Florida-Specific SPFs Calibrated to Florida Data for Urban and Rural Two-Way, Two-Lane Segments: Total and F+I Crashes

	Calibrated Florida-Specific Full SPFs-MLE Negative Binomial									
	Intercept		log(AADT)		Speed Limit		Segment Length			
Severity	Estimate	*P*-Value	Estimate	*P*-Value	Estimate	*P*-Value	Estimate	*P*-Value	Dispersion (*k*)	Deviance
Urban										
Total	−7.9825	<.0001	1.0048	<.0001	−0.0303	<.0001	0.8677	<.0001	0.4871	1,079.69
PDO	−6.0358	<.0001	0.8957	<.0001	−0.0160	<.0001	1.1044	<.0001	0.8150	1,409.71
F+I	−7.1871	<.0001	1.1359	<.0001	−0.0396	<.0001	0.7348	<.0001	0.8413	1,305.30
Rural										
Total	−11.4845	<.0001	1.0837	<.0001	0.0287	<.0001	0.6140	.0131	0.6725	1,006.80
PDO	−12.8075	<.0001	1.2084	<.0001	0.0146	<.0001	0.5794	<.0001	0.2313	1,040.75
F+I	−11.5280	<.0001	1.0119	<.0001	0.0312	<.0001	0.7921	.0016	0.3414	1,004.15

and rural two-way, two-lane roadway segments. In the full SPF, log (AADT), speed limit, and length of segment were the most significant variables in the final models of total crashes and F+I crashes.

Bayesian Approach Versus EB Method

The Bayesian approach has been gaining more interest recently in the before–after roadway safety literature in univariate and multivariate settings, for several reasons: (*a*) Bayesian models account for the uncertainty associated with parameter estimates and provide exact measures of uncertainty of the posterior distributions of the parameters, and hence they overcome the maximum likelihood method's problem of overestimating precision because of ignoring this uncertainty and in some cases crash data are characterized by low sample mean values and small sample sizes; (*b*) valid crash models can be estimated with a small sample size because of the Bayesian properties, which might be the case for most road safety benefit analyses; and (*c*) Bayesian inference can effectively avoid the problem of overfitting that occurs when the number of observations is limited and the number of variables is large. Lord and Mannering have discussed the limitations and the adverse effects of small sample sizes with the use of the maximum likelihood estimate approach (*20*). The Bayesian approach also requires prior information, but instead of a point estimate of the expected mean and variance as in the EB method, a prior distribution of probable values is required. There are different types of priors used in the Bayesian estimation: noninformative (flat prior), low-informative, and informative priors. Vague or low-informative priors have been used widely in the literature. The EB method treats the parameters of the models as fixed, unknown constants, and the data are used solely to best estimate the unknown values of the parameters. In the Bayesian approach, the parameters are treated as random variables, and the data are used to update beliefs about the behavior of the parameters to assess their distributional properties. The interpretation of Bayesian inference is slightly different from the classical statistics; the Bayesian derives updated posterior probability of the parameters and constructs credibility intervals that have a natural interpretation of probabilities. Moreover, in the before–after framework, the Bayesian method integrates the EB two steps into one by calculating the odds ratio and the SPFs in a single step, and hence, integrating any error or variance of the estimated regression coefficient into the final estimates of the safety effectiveness of a treatment. Most important, the flexibility of a Bayesian formulation allows for different model specifications; therefore it is possible to account for various levels of correlation. Many studies have proved from different aspects that it is beneficial to analyze multilevel crashes (e.g., single-vehicle versus multivehicle crashes and different injury severity levels) separately while considering their correlation effects (*21–26*). Ma and Kockelman used a multivariate Poisson model to simultaneously analyze crash counts with different injury severity levels through the Bayesian paradigm, providing a systematic approach to estimating correlated count data (*27*). Recently, more-advanced multivariate Poisson–lognormal models have been adopted to analyze correlated count data. Multivariate Poisson–lognormal models were argued to be superior to multivariate Poisson models because of their capability to account for overdispersion and because their more general correlation structure allows for negative correlations. Several studies have used multivariate Poisson–lognormal models that can simultaneously analyze crash frequencies of different severities or crash types (*28–30*). In this study, a simplified multivariate Poisson–lognormal model, the Bayesian bivariate Poisson–lognormal model (BVPLN), is used to analyze crash frequencies by two severity levels: F+I and PDO. The BVPLN is generalized to incorporate a change-point model that can analyze before–after data with the identified comparison group of sites.

Modeling Framework for Bayesian BVPLN Before–After Model

In the BVPLN model, the crash frequency Y_{it} has a Poisson distribution conditional on the σ-field generated by the random variables of unobserved heterogeneity ε_1 and ε_2 and the set of exposure factors e_{it} and independent explanatory variables X_{it} (*30*). The model can be set up as follows:

$$Y_{it} \sim \text{Poisson}\left(\lambda_{it} \text{ for } i = 1, 2, \ldots, m \text{ and } t = 1, 2, \ldots, n\right) \tag{1}$$

where Y_{it} is the observed crash count at segment *i* in year *t* with the underlying Poisson mean λ_{it} (i.e., the expected crash frequency) for segment *i* in year *t*. AADT values and segment length are commonly used as exposure variables with an underlying assumption of a linear relationship with the crash count. AADT values and segment length do not explain the risk of crashes and hence are not cause–effect covariates. A sensitivity analysis was conducted between crash frequency and each AADT value and segment length. The sensitivity analysis revealed that the relationship between crash frequency and AADT and segment length is nonlinear. AADT value and segment length are retained in the predictive model to enhance the estimation as suggested by Hauer et al. (*31*). The Poisson rate is modeled as a function of the log link with the use of a lognormal distribution:

$$\log \lambda_{it} = \log e_{it} + X'_{it}\beta + \varepsilon_{it} \tag{2}$$

The random errors ε_1 and ε_2 are assumed jointly normally distributed with $(\varepsilon_1, \varepsilon_2) \sim N\{(0, 0), (\sigma_1^2, \rho\sigma_1\sigma_2, \sigma_2^2)\}$ where ρ is the correlation coefficient.

Model Estimation

The BVPLN models were estimated for urban and rural segments with a Bayesian approach. In the model estimation, with no prior knowledge of the parameters' likely range of values, noninformative priors were specified for the parameters. The random effect ε_{it} is unknown and therefore has its own prior distribution, $p(\varnothing)$. The joint prior distribution is (*32*)

$$p(\varnothing,\theta) = p(\varnothing)p(\theta|\varnothing) \tag{3}$$

where θ is the vector of unknown parameters and the joint posterior distribution can be defined as

$$p(\varnothing,\theta|y) \propto p(\varnothing,\theta)p(y|,\varnothing\theta) = p(\varnothing,\theta)p(y|\theta) \tag{4}$$

These posterior distributions were calibrated by the Monte Carlo Markov chain with the use of all of the data for the comparison group sites and the before period data for the treated sites (*33*). For each model, three chains of 20,000 iterations were set up in WinBUGS, and 5,000 iterations were used in the burn-in step (*34*). Convergences of the models were checked by monitoring the Monte Carlo Markov chain trace plots for the model parameter; if all values were in a zone without strong periodicities or tendencies, the model was considered convergent. The deviance information criterion (DIC), a Bayesian generalization of Akaike's information criterion, is used to measure the model complexity and fit (*35*). The DIC is calculated as follows:

$$\text{DIC} = \bar{D} + p_D \tag{5}$$

where

$\bar{D}$ = measure of model fitting,
p_D = effective number of parameters, and
DIC = combination of the two measures.

A smaller DIC indicates a better model fitting. According to Spiegelhalter et al., a difference greater than 10 can rule out the model with a higher DIC; differences between five and 10 are considered substantial (*35*).

RESULTS AND DISCUSSION

The observational before–after naive approach was applied on the 41 and 43 sites totaling 8.58 and 32.81 mi for urban and rural two-way, two-lane roadway segments, respectively, that were upgraded to four-lane divided roadways. The evaluation of the safety effectiveness here is estimated for two major countermeasures: adding a through lane and adding a raised median at the same time. For the 41 and 43 treated urban and rural two-lane sites, respectively, crash rates were calculated with the mean AADT and length of the segment. The crash modification factors were estimated on the basis of crash rates for individual locations and all locations combined, and the Poisson test of significance was performed.

Overall, the total crash rate across all locations for urban roadways was reduced from 24.79 crashes per million vehicle miles (MVM) to 6.96 crashes per MVM after a lane was added and the roadway was divided with a raised median, representing about a 71.5% reduction in the total crash rate. The reduction of the total crash rate was statistically significant. For rural two-way, two-lane roadways, the crash rate dropped from 26.18 crashes per MVM to 16.66 crashes per MVM; the estimated safety effectiveness was 36.35%. The same approach was applied to F+I crashes only; the conversion of two-lane roadways to four-lane divided roadways reduced F+I crashes by 48.42% and 34.98% for urban and rural areas, respectively.

With the use of SAS 9.3, a procedure to apply the observational before–after with the comparison group was developed. The procedure was applied on the same 41 and 43 sites mentioned in the previous section. The safety effectiveness of adding a lane and installing a median was estimated for each site separately and for all sites combined for roadway segments with the use of crash experience data from 381 and 370 comparison locations totaling 67.81 and 230.33 mi for urban and rural two-lane roadways, respectively. For example, the safety effectiveness for urban two-lane roadways across all locations was significantly improved by 64.49% and with a standard error of 9.94% for total crashes (all severity). The statistical significance of the estimated safety effectiveness was calculated as follows:

$$\text{Abs}\left(\frac{\text{safety effectiveness}}{\text{SE}(\text{safety effectiveness})}\right) = \frac{64.49}{9.94} = 6.49 \tag{6}$$

where Abs is absolute value and SE is standard error.

Since Abs [safety effectiveness/SE(safety effectiveness)] ≥ 1.96, it can be concluded that the treatment effect is significant at the 95% confidence level. Tables 4 and 5 present the final results for urban and rural total crashes and PDO and F+I crashes and compares them with other crash modification factors that were estimated with different methods.

TABLE 4 Comparison of Naive, Comparison Group, EB, and Bayesian Methods: Safety Effectiveness of Conversion of Urban and Rural Two-Lane Roadways to Four-Lane Divided Roadways

					Before–After with EB				Before–After with Bayesian	
	Naive Before–After		Before–After with Comparison Group		Simple SPF–NB		Full SPF–NB		Bayesian	
Severity	CMF (Safety Effectiveness)	SE	CMF (Safety Effectiveness)	SE	CMF (Safety Effectiveness)	SE	CMF (Safety Effectiveness)	SE	CMF (Safety Effectiveness)	SE
Urban Crashes										
Total	0.28 (71.43%)	0.09 (9.32%)	0.35 (64.49%)	0.10 (9.94%)	0.32 (67.70%)	0.08 (8.04%)	0.35 (64.80%)	0.09 (8.76%)	0.34 (65.88%)	0.09 (9.05%)
PDO	0.41 (58.77%)	0.11 (11.23%)	0.37 (63.46%)	0.12 (11.56%)	0.31 (67.78%)	0.11 (10.63%)	0.35 (65.06%)	0.09 (8.70%)	0.35 (64.89%)	0.09 (8.91%)
F+I	0.52 (48.42%)	0.10 (9.86%)	0.36 (64.37%)	0.10 (9.72%)	0.33 (67.03%)	0.09 (8.94%)	0.36 (64.34%)	0.09 (8.81%)	0.37 (63.27%)	0.09 (8.87%)
Rural Crashes										
Total	0.64 (36.35%)	0.11 (10.54%)	0.73 (27.26%)	0.10 (9.94%)	0.71 (29.48%)	0.09 (9.04%)	0.74 (25.87%)	0.09 (9.4%)	0.71 (28.79%)	0.08 (7.65%)
PDO	0.61 (38.77%)	0.10 (9.92%)	0.69 (30.72%)	0.10 (9.85%)	0.70 (29.89%)	0.08 (8.41%)	0.71 (28.75%)	0.08 (8.10%)	0.69 (30.88%)	0.08 (7.89%)
F+I	0.65 (34.97%)	0.09 (8.77%)	0.54 (46.12%)	0.09 (8.94%)	0.59 (40.24%)	0.09 (8.88%)	0.51 (49.42%)	0.07 (7.19%)	0.55 (45.13%)	0.08 (8.24%)

NOTE: CMF = crash modification factor; SE = standard error.

TABLE 5 CMF and Safety Effectiveness of the Conversion of Urban and Rural Two-Lane Roadways to Four-Lane Divided Roadways by AADT

		Full SPF–NB		Univariate Poisson–Lognormal	
Number of Crash Sites	Traffic Volume After Period (AADT)	CMF (Safety Effectiveness)	SE	CMF (Safety Effectiveness)	SE
Urban					
26	AADT ≥ 18,000 vpd	0.23 (76.40%)	0.07 (7.21%)	0.26 (73.86%)	0.08 (7.77%)
15	AADT < 18,000 vpd	0.46 (53.36%)	0.18 (17.95%)	0.47 (52.01%)	0.15 (15.24%)
Rural					
18	AADT ≥ 10,000 vpd	0.71 (28.59%)	0.11 (11.03%)	0.71 (28.72%)	0.10 (10.23%)
25	AADT < 10,000 vpd	0.79 (21.04%)	0.18 (17.73%)	0.80 (10.19%)	0.16 (16.18%)

The observational before–after with the EB method was applied on the aforementioned treated sites with the use of SAS 9.3 statistical software. The safety effectiveness of adding a lane and installing a raised median was estimated with full and simple SPFs and the observed crash history of the individual treatment sites, and then the overall safety effectiveness was estimated with Equation 10. For example, the safety effectiveness of the conversion of urban two-lane to four-lane divided roadways across all locations was significantly improved by 64.80% (±8.76%) with the full SPF, while the safety effectiveness was estimated to be 67.70% (±8.04) with the simple SPF. The EB method with the use of the full and simple SPFs was applied to urban and rural roadway segments for total, PDO, and F+I crashes.

To overcome some of the EB limitations, the before–after with the Bayesian method was also carried out with the use of the freeware WinBUGS. Univariate Poisson–lognormal and BVPLN models shown in Table 6 with Bayesian inferences were estimated with data from the comparison group sites and the treated sites in the before period. The safety effectiveness of adding a lane and installing a raised median was estimated with the use of the expected crashes

TABLE 6 Florida-Specific Univariate and Bivariate Poisson–Lognormal Models Calibrated to Florida Data for Urban and Rural Two-Way, Two-Lane Segments: Total, PDO, and F+I Crashes

	Urban 2-Way 2-Lane Segments[a]				Rural 2-Way 2-Lane Segments[b]			
	Mean	SD	2.5%	97.5%	Mean	SD	2.5%	97.5%
Univariate Poisson–Lognormal								
Total crash intercept	–7.451	0.394	–8.342	–6.412	–10.125	0.476	–10.942	–9.178
log(AADT)	0.924	0.051	0.847	1.066	0.976	0.049	0.876	1.075
Speed limit	–0.030	0.029	–0.037	–0.028	–0.023	0.002	–0.024	–0.021
Segment length	0.753	0.045	0.667	0.849	0.813	0.144	0.567	1.127
Multivariate Poisson–Lognormal								
PDO crash intercept	–7.192	0.394	–7.992	–6.530	–9.982	0.476	–10.423	–9.271
log(AADT)	1.073	0.052	0.934	1.222	1.107	0.064	0.978	1.201
Speed limit	–0.0385	0.003	–0.039	–0.028	–0.023	0.002	–0.027	–0.020
Segment length	0.727	0.043	0.668	0.841	0.584	0.131	0.467	0.815
σ_{11}	0.112	0.095	0.097	0.187	0.231	0.098	0.143	0.365
Fatal and injury crash intercept	–6.041	0.201	–6.156	–5.008	–10.476	0.762	–11.328	–9.471
log(AADT)	0.879	0.022	0.802	0.967	0.804	0.364	0.435	1.286
Speed limit	–0.015	0.001	–0.017	–0.013	0.033	0.012	0.022	0.044
Segment length	0.982	0.011	0.878	1.304	0.822	0.084	0.758	0.914
σ_{12}	0.210	0.039	0.129	0.387	0.246	0.056	0.214	0.341
σ_{22}	0.329	0.097	0.315	0.396	0.234	0.075	0.149	0.370

NOTE: SD = standard deviation.
[a]Univariate Poisson–lognormal DIC = 954.251. Multivariate Poisson–lognormal: correlation = 0.54; DIC = 89.354.
[b]Univariate Poisson–lognormal DIC = 864.846. Multivariate Poisson–lognormal: correlation = 0.47; DIC = 83.148.

from the univariate Poisson–lognormal for total crashes and the BVPLN models for PDO and F+I crashes on the individual treatment sites. Then the overall safety effectiveness was estimated with Equation 8. For example, the safety effectiveness of the conversion of urban two-lane to four-lane divided roadways across all locations was significantly improved by 65.88% (±9.05%) with the Bayesian modeling technique. To compare Bayesian with other observational before–after methods, the Bayesian method was applied to urban and rural roadway segments for total, PDO, and F+I crashes. Table 4 summarizes the results from the four approaches: naive before–after, before–after with comparison group, before–after with EB, and before–after with full Bayes.

The results from the naive method overestimated the treatment effects for total crashes on urban two-lane roads and PDO crashes on rural two-lane roads, possibly as a result of regression-to-the-mean bias. The naive before–after analysis underestimated the safety effectiveness for F+I crashes for urban and rural two-lane roads; it is well-known that the naive before–after study cannot distinguish the effect of treatment from other extraneous factors that might change from the before to the after period (*20*). Results from the before–after with the comparison group are almost identical to the full SPF EB. The full SPF EB method required more roadway geometry data for the treatment sites. The comparison group method returned results similar to the EB method with a slightly higher standard error. Compared with the before–after with the comparison group, the simple SPF and full SPF EB methods provided the least standard error. The Bayesian method provided results very comparable with the EB method with fewer data requirements. Moreover, the Bayesian method integrated the two-step EB into one, which is deemed to be more efficient to account for the uncertainty in the crash data through integrating any error or variance of the estimated regression coefficient into the final estimates of the safety effectiveness of a treatment.

To evaluate the safety effectiveness of two- to four-lane conversions at different traffic volume levels, the EB with full SPF and Bayesian methods were applied to the treated sites with high and low traffic volumes (AADT) [with arbitrary thresholds; e.g., ≥18,000 vehicles per day (vpd) and <18,000 vpd for urban, and ≥10,000 vpd and <10,000 vpd for rural]. These arbitrary thresholds were chosen to achieve an adequate sample size in both levels. The 18,000 vpd and 10,000 vpd were close to the median AADT values in the after period for the treated urban and rural roadway segments, respectively. Table 5 indicates that the two-lane to four-lane divided conversion would result in a better crash per mile reduction for roadway segments with higher AADT. For example, from the EB method in urban areas upgrading two-lane roadways to four-lane divided was 76.40% (±7.21%) effective in reducing crashes with an AADT ≥18,000 vpd; the safety effectiveness was only 53.36% (±17.95%) with an AADT <18,000 vpd. Also, results suggest that the reduction of crashes appears to be increasing slightly as AADT increases for rural roadway segments. The two- to four-lane conversion of rural roadways resulted in a crash reduction of 28.59% (±11.03%) with an AADT ≥10,000 vpd, and 21.04% (±17.73%) for an AADT <10,000 vpd.

The standard errors for less congested urban and rural roadways are higher than for congested roadways; that finding may indicate that the two-lane to four-lane conversion is statistically more significant in decreasing crashes on roadways with a high AADT. It also implies that widening and providing physical separation are essential to improve safety on congested urban and rural roadways. The results from the Bayesian method were comparable with the EB method.

CONCLUSION

Addressing the safety of upgrading two-lane roadways to four-lane divided roadways is a vital step toward achieving the overall goal of the AASHTO strategic highway safety plan of reducing fatalities on U.S. roads. Statistics from the Fatalities Analysis Reporting System reveal that in 2010 approximately 54% of the 30,862 total fatal crashes occurred on two-lane roadways (*22*). With the use of data collected in the state of Florida, the safety implications of upgrading two-lane roadways to four-lane divided roadways were evaluated. The various observational before–after analyses ranged from naive, before–after with comparison group, EB, and FB methods implemented to assess changes in safety (in regard to the reduction in the number of total and severe crashes). The naive before–after method suffered from an over- and underestimation of the safety effectiveness of the treatment. The before–after with comparison group provided results similar to those of the full SPF EB method with a slightly higher standard error; this approach required comparison sites with characteristics similar to the treated sites. The EB method requires SPFs to be calibrated with the reference group of sites. In this study, two sets of SPFs were calibrated: the full and simple SPFs for total and severe crashes on the basis of roadway and traffic characteristics and on the basis of AADT only, respectively. Using the full SPF provided slightly better results in regard to a lower standard error and a better statistical fit than the commonly used simple SPFs. Apart from the improvement in goodness of fit, the prediction capability of SPFs can be improved when the model is calibrated with geometric and other traffic characteristics (e.g., speed limit). The past decade has witnessed a revolutionary advancement in statistical modeling techniques, and the Bayesian approach is among the most notable for its superior performance and modeling flexibility. Another important goal of this study was to compare the commonly used *Highway Safety Manual* procedure, comparison group, and EB with all their data requirements and the FB method. The finding from this study depicts that the intensive data requirements to perform the before–after with the EB method can be relaxed by implementing the FB approach. The FB provided results comparable with the commonly used HSM methods. The Bayesian BVPLN model indicates that there is a correlation between different severity levels (PDO and F+I), with correlation coefficients of .54 and .47 for the urban and rural two-lane roadways, respectively. The before–after with Bayesian BVPLN might be a promising technique to obtain a reliable estimate of the expected crashes at a specific group of treated sites, especially when relatively scarce information about the treated sites is available in the case of low traffic volumes or when only a few years of crash data is available. In this study the conversion of two-lane roadways to four-lane divided roadways showed a statistically significant reduction in total and severe crashes. It can also be concluded that the treatment is more effectual on urban than on rural roadway segments. There was a notable reduction of more than 63% on urban roadways compared with a 45% reduction on rural roadways for F+I crashes. Conversion to a four-lane divided roadway yielded a higher reduction in total and PDO crashes in urban areas than in rural areas. The safety effectiveness was found to be about 65% for total and PDO crashes on urban roadways, while it was about 30% in rural areas. The crash reduction appeared to be even more effective for sites having a higher AADT. Two-lane to four-lane divided roadway conversion showed better safety effects on total crashes on sites with an AADT >10,000 vpd and 18,000 vpd for rural and urban roadway segments, respectively. This finding can be explained by the fact that once additional capacity is provided through adding lanes, the density is decreased, providing a more forgiving driving environment. This forgiving driving environment was found to be more effective in congested urban roadways. In the future, the safety effectiveness of the conversion of two-lane to four-lane divided should be reevaluated with more after years and when the projected traffic is reached.

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REFERENCES

1. *Highway Capacity Manual 2010.* Transportation Research Board of the National Academies, Washington, D.C., 2010.
2. *Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users, Public Law 109-59.* 2007. http://www.gpo.gov/fdsys/pkg/PLAW-109publ59/pdf/PLAW-109publ59.pdf. Accessed June 28, 2013.
3. Kononov, J., B. Bailey, and B. Allery. Exploratory Analysis of Relationship between the Number of Lanes and Safety on Urban Freeways. Presented at 87th Annual Meeting of the Transportation Research Board, Washington, D.C., 2008.
4. *2005–2007 Three Year Crash Rates.* Traffic Engineering and Safety Branch, North Carolina Department of Transportation, Raleigh.
5. Williams, K., and V. Stover. *Access Management Manual.* Transportation Research Board of the National Academies, Washington, D.C., 2003.
6. Noland, R. B., and L. Oh. The Effect of Infrastructure and Demographic Change on Traffic-Related Fatalities and Crashes: A Case Study of Illinois County-Level Data. *Accident Analysis and Prevention,* Vol. 35, No. 4, 2004, pp. 525–532.
7. Abdel-Aty, M., and A. Radwan. Modeling Traffic Accident Occurrence and Involvement. *Accident Analysis and Prevention,* Vol. 32, No. 5, 2000, pp. 633–642.
8. Council, F. M., and J. R. Stewart. *Safety Effects of the Conversion of Rural Two-Lane to Four-Lane Roadways Based on Cross-Sectional Models.* FHWA-990327. FHWA, U.S. Department of Transportation, 2000.
9. Aul, N., and G. A. Davis. Use of Propensity Score Matching Method and Hybrid Bayesian Method to Estimate Crash Modification Factors of Signal Installation. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1950,* Transportation Research Board of the National Academies, Washington, D.C., 2006, pp. 17–23.
10. Pawlovich, M. D., W. Li, A. Carriquiry, and T. M. Welch. Iowa's Experience with Road Diet Measures: Use of Bayesian Approach to Assess Impacts on Crash Frequencies and Crash Rates. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1953,* Transportation Research Board of the National Academies, Washington, D.C., 2006, pp. 163–171.
11. Lan, B., B. Persaud, C. Lyon, and R. Bhim. Validation of a Full Bayes Methodology for Observational Before-After Road Safety Studies and Application to Evaluation of Rural Signal Conversions. *Accident Analysis and Prevention,* Vol. 41, No. 3, 2009, pp. 574–580.
12. Persaud, B., B. Lan, C. Lyon, and R. Bhim. Comparison of Empirical Bayes and Full Bayes Approaches for Before–After Road Safety Evaluations. Presented at 88th Annual Meeting of the Transportation Research Board, Washington, D.C., 2009.
13. El-Basyouny, K., and T. Sayed. A Full Bayes Multivariate Intervention Model with Random Parameters Among Matched Pairs for Before–After Safety Evaluation. *Accident Analysis and Prevention,* Vol. 43, No. 1, 2011, pp. 87–94.
14. Florida Department of Transportation. *Financial Management Database.* http://webapp01.dot.state.fl.us/FinancialProjectSearch. Accessed Oct. 2012.
15. Pendleton, O. *Application of New Crash Analysis Methodologies: Volume 1—General Methodology.* Texas Transportation Institute, Texas A&M University System, College Station, 1991.
16. Hauer, E. *Observational Before–After Studies in Road Safety.* Pergamon Publications, London, 1997.
17. Kononov, J., and B. Allery. Level of Service of Safety, Conceptual Blueprint and Analytical Framework. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1840,* Transportation Research Board of the National Academies, Washington, D.C., 2003, pp. 57–66.
18. Shen, Q. *Development of Safety Performance Functions for Empirical Bayes Estimation of Crash Reduction Factors.* PhD dissertation. Florida International University, Miami, 2007.
19. SAS Institute Inc. *The GENMOD Procedure.* Cary, N.C. http://support.sas.com/onlinedoc/913/docMainpage.jsp. Accessed April 2013.
20. Lord, D., and F. Mannering. The Statistical Analysis of Crash-Frequency Data: A Review and Assessment of Methodological Alternatives. *Transportation Research, Part A,* Vol. 44, 2010, pp. 291–305.
21. Fitzpatrick, K., W. Schneider IV, and E. Park. *Comparisons of Crashes on Rural Two-Lane and Four-Lane Highways in Texas.* Report No. FHWA/TX-06/0-4618-1. 2005.
22. National Highway Traffic Safety Administration. *Fatality Analysis Reporting System.* U.S. Department of Transportation, 2010. http://www.fars.nhtsa.dot.gov. Accessed June 28, 2013.
23. Ivan, J., C. Wang, and N. Bernardo. Explaining Two-Lane Highway Crash Rates Using Land Use and Hourly Exposure. *Accident Analysis and Prevention,* Vol. 32, 2000, pp. 787–795.
24. Qin, X., J. Ivan, and N. Ravishanker. Selecting Exposure Measures in Crash Rate Prediction for Two-Lane Highway Segments. *Accident Analysis and Prevention,* Vol. 36, 2004, pp. 183–191.
25. Ye, X., R. Pendyala, S. Washington, K. Konduri, and J. Oh. A Simultaneous Equations Model of Crash Frequency by Collision Type for Rural Intersections. *Safety Science,* Vol. 47, 2009, pp. 443–452.
26. Geedipally, S., and D. Lord. Investigating the Effect of Modeling Single-Vehicle and Multi-Vehicle Crashes Separately on Confidence Intervals of Poisson-Gamma Models. *Accident Analysis and Prevention,* Vol. 42, 2010, pp. 1273–1282.
27. Ma, J., and K. M. Kockelman. Bayesian Multivariate Poisson Regression for Models of Injury Count, by Severity. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1950,* Transportation Research Board of the National Academies, Washington, D.C., 2006, pp. 24–34.
28. Park, E. S., and D. Lord. Multivariate Poisson–Lognormal Models for Jointly Modeling Crash Frequency by Severity. In *Transportation Research Record: Journal of the Transportation Research Board, No. 2019,* Transportation Research Board of the National Academies, Washington, D.C., 2007, pp. 1–6.
29. Ma, J., K. Kockelman, and P. Damien. A Multivariate Poisson–Lognormal Regression Model for Prediction of Crash Counts by Severity, Using Bayesian Methods. *Accident Analysis and Prevention,* Vol. 40, 2008, pp. 964–975.
30. El-Basyouny, K., and T. Sayed. Collision Prediction Models Using Multivariate Poisson-Lognormal Regression. *Accident Analysis and Prevention,* Vol. 41, 2009, pp. 820–828.
31. Hauer, E., F. M. Council, and Y. Mohammedshah. Safety Models for Urban Four-Lane Undivided Road Segments. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1897,* Transportation Research Board of the National Academies, Washington, D.C., 2004, pp. 96–105.
32. Munkin, M., and P. Trivedi. Simulated Maximum Likelihood Estimation of Multivariate Mixed-Poisson Regression Models, with Application. *Econometrics Journal,* Vol. 2, 2002, pp. 29–48.
33. Gelman, A., J. Carlin, H. Stern, and D. Rubin. *Bayesian Data Analysis.* CRC Press, New York, 2004.
34. Lunn, D. J., A. Thomas, N. Best, and D. Spiegelhalter. WinBUGS–A Bayesian Modelling Framework: Concepts, Structure, and Extensibility. *Statistics and Computing,* Vol. 10, 2000, pp. 325–337.
35. Spiegelhalter, D., A. Thomas, N. Best, and D. Lunn. *Winbugs User Manual.* MRC Biostatistics Unit, Cambridge, United Kingdom, 2003.

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