Safety Evaluation of Discontinuing Late Night Flash Operations at Signalized Intersections

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This study examined the safety impacts of converting late nighttime flash (LNF) to normal phasing operation at signalized intersections using the empirical Bayes (EB), the univariate Full Bayesian (FB), and multivariate FB before-after methods. Data were obtained from the North Carolina Department of Transportation for 61 treatment sites and 395 reference intersections that remained on LNF operation from 2000 to 2007.

The results from the EB method are almost identical to those of the univariate FB. The FB method offered more flexibility in selecting the functional form of expected crashes at similar sites (similar to the SPF in the EB), and addressing uncertainty in the data. Compared to the univariate FB, the multivariate FB using the multivariate poisson lognormal model (MVPLN) provided better results based on much lower deviance information criterion (DIC) values. The MVPLN model was favored and the recommended CRFs are 48% (±6%), 53% (±8%), and 57% (±7%) for nighttime total, injury and fatal, and frontal impact crashes, respectively.
BACKGROUND

During late night flash (LNF) mode (from late night to early morning hours), traffic signals flash yellow for one road (typically, the major road) requiring caution but no stopping, and flash red for the other road (typically, the minor road) requiring drivers to stop and then proceed through the intersection after yielding to the traffic on the major road. The intent of LNF is to reduce energy consumption and delay during periods of low traffic demand. However, in recent years, many agencies have started replacing LNF with normal phasing operation due to concerns over safety.

The safety impacts of removing LNF (and replacing with normal phasing operation) have been studied since the 1980’s (1, 2). Gaberty and Barbaresso (2) analyzed accident data at 59 four-leg intersections in Oakland County, Michigan, where the nighttime flash mode was replaced with normal phasing operation between 1980 and 1985. Results indicated a 91% reduction in angle crashes and 95% reduction in injury right-angle crashes. Barbaresso (1) also found that right-angle crashes decreased dramatically after the conversion. However, it was not clear in these studies whether high-accident locations were selected for the change or whether the results may have been biased due to regression to the mean (RTM).

Polanis (3) evaluated the safety of removing LNF from 19 sites in Winston-Salem, NC, using a naïve before after method and concluded that night time right angle crashes decreased by 78%. Srinivasan et al. (4) conducted a safety evaluation of LNF conversion for 12 intersections in Winston-Salem, NC. They employed the before-after empirical Bayes (EB) method that included the use of data from 75 reference sites in order to address the possible bias due to RTM. They concluded that night time crashes decreased by 35% and night time angle crashes decreased by 34%. More recently, Murphy (5) conducted an evaluation of 67 intersections in North Carolina where LNF was removed starting from 2003. The evaluation method was a before-after EB using the method of sample moments. The reference group included 467 intersections that operated in LNF mode and had not been modified during the study period. Murphy (5) found that for sites where LNF was discontinued, there was a 27% reduction in night crashes, 23% reduction in injury and fatal crashes, and 48% reduction in frontal impact crashes. Murphy (5) did not use data on traffic volumes in his evaluation.

Based on the results from previous studies, it seems clear that removing LNF (and replacing with normal phasing operation) will reduce crashes at night. However, the magnitude of the reduction seems to vary significantly ranging from as low as 27% (5) to as high as 78% (3). The objective of this effort is to evaluate the effect of eliminating LNF operations at signalized intersections using the common state of the art EB method and the more advanced full Bayes (FB) methods. This is a before-after evaluation using data from signalized intersections in North Carolina.

This paper is structured as follows. It starts with an overview of analysis methods for conducting before-after evaluations. Both the EB method and FB method are discussed. This is followed by a brief discussion of the data including summary information about treatment sites (where LNF was removed) and comparison/reference sites that remained on LNF mode during
the study period. This is then followed by results of the evaluation from both the EB and FB methods. The paper ends with some discussion and conclusions.

3 OVERVIEW OF ANALYSIS METHODS

For the past two decades, the EB method has been used successfully to conduct before-after evaluations (6). To evaluate safety treatments with the EB approach, the before period crash experience at treated sites is used in conjunction with a negative binomial crash prediction model for untreated reference sites to estimate the expected number of crashes that would have occurred without treatment. This estimate is compared to the crashes observed after treatment to evaluate the effect of the treatment. This approach accounts for possible bias due to RTM that can result from the natural tendency to select high crash locations for treatment.

With the availability of the software package WinBUGS (7), Bayesian method, also called the fully Bayesian (FB) approach has been suggested by a few recent studies (8-11) as a useful alternative to the EB approach for the following reasons. FB can be applied even if the reference group is limited. FB is also better at accounting for uncertainty in data used, and provides more detailed causal inferences and more flexibility in selecting crash count distributions. In addition, it can more explicitly account for spatial correlation and correlation between crash types. Following is an overview of both the EB and FB methods.

The EB Method

To overcome the drawbacks of the conventional before-after study techniques, the empirical Bayes (EB) approach was developed to evaluate the effects of road safety treatments. Hauer (12) was among the first researchers to indicate how the EB method eliminates the effects of RTM in road crash data. Since then, the EB approach has been suggested, examined and widely explored by several researchers (6, 13, 14).

Overview of Procedure

The EB procedure (13, 14) seeks to estimate the long-term expected crash frequency ($\lambda$) by accounting for the possible bias due to RTM. One of the first steps is estimating a safety performance function (SPF) using data from a reference group of untreated sites. Typically, the SPF is estimated as a negative binomial (NB) regression model. For a negative binomial (NB) model, the expected number of crashes is gamma distributed with shape parameter $k$, and the recorded number of crashes $y_i$ for each entity is Poisson distributed. In the EB method, $\lambda$ is estimated as the weighted average of the before period crash count at the treatment sites and the expected number of crashes based on the SPF. The weight $\alpha_i$ which is used to combine observed crash at site $i$ and estimated expected crashes for similar entities based on the SPF, can be calculated as:

$$\alpha_i = \frac{1/k}{1/k + \mu_i} \quad (1)$$
$1 - \alpha_i = \frac{\mu_i}{I/k + \mu_i}$  \hspace{1cm} (2)

where:

- $\mu_i$ = expected crashes in n years at similar sites, estimated from safety performance functions (SPFs) and annual calibration factors to account for variations in weather, demography, and crash patterns during the study period,
- $k$ = the over-dispersion parameter of the NB model and is estimated from the SPF calibration process.

The expected crashes for a specific site can be estimated as:

$$\lambda_i = E(\mu_i|y_i) = \alpha_i\mu_i + (1 - \alpha_i)y_i$$  \hspace{1cm} (3)

where:

- $\lambda_i$ = expected crash counts in n years at site i, and
- $y_i$ = observed crash counts in n years at site i

The estimate of $\lambda$ is then summed over all sites in a treatment group of interest (to obtain $\lambda_{sum}$) and compared with the count of crashes during the after period in that group ($\pi_{sum}$). The variance of $\lambda$ is also summed over all sections in the treatment group. The index of effectiveness ($\theta$), also called as the crash modification factor (CMF) is estimated as:

$$\theta = (\pi_{sum}/\lambda_{sum})/[1 + [Var(\lambda_{sum})/\lambda_{sum}^2]]$$  \hspace{1cm} (4)

The crash reduction factor (CRF) is $100(1-\theta)$.

The standard deviation of $\theta$ is given by:

$$Std\text{dev}(\theta) = \left(\frac{\theta^2[Var(\pi_{sum})/\pi_{sum}^2] + [Var(\lambda_{sum})/\lambda_{sum}^2]}{[1 + \frac{Var(\lambda_{sum})}{\lambda_{sum}^2}]^2}\right)^{0.5}$$  \hspace{1cm} (5)

Applications and limitations

The EB method for the treatment effect analysis has been extensively evaluated and found to be able to provide promising results (6, 13, 14). It is now widely used to develop crash modification factors (CMFs) (15, 16, 17), and the recently published Highway Safety Manual (HSM) (18) recommends its use for conducting before-after evaluations. However, there are still some limitations of the EB method:

- It requires a large data set to develop reliable SPFs.
- It has limited flexibility in selecting the underlying distribution for the crash frequency. In its current form, only the NB distribution can be used, even if other distributions may be more appropriate for the data.
- Only point estimates of expected crashes are available, and hence the uncertainty of the estimate is not explicitly considered in the analysis.
- In its current form, the EB method cannot handle multivariate analysis. This can be an issue if evaluations of multiple crash types are examined and they are correlated.
• With EB, it is very difficult to incorporate spatial correlation in the analysis.

The FB method is able to overcome these limitations and is discussed below:

The FB Method

Similar to the EB method, the FB method utilizes an untreated reference group data to make inferences and to account for possible effects unrelated to the treatment. However, unlike the EB method, the FB method also includes data from the before period of treated sites to develop inferential models.

Since the intent is to use the FB method in before-after studies, it is necessary to find an appropriate way to model the effect of time. There are at least four ways to model the “time effect” using the FB method: Poisson autoregressive (AR) model combining time effects and random effects together by an AR model; time trend model, time multiplier model; time varying coefficients model where all the coefficients are considered time varying. The Poisson AR model cannot be used if the countermeasure implementation year is excluded from the analysis.

Previous research by Lan and Persaud (19, 20) on using FB methods for before-after evaluation and network screening found that time varying coefficients model were not very effective or useful because it introduced too many parameters into the model. The other two models, time trend and time multiplier models, were found to be more useful. Both univariate and multivariate FB methods with the two time effects models were explored in the study. Following is further discussion about univariate and multivariate FB models.

Univariate FB method

The following model is a typical univariate FB model framework:

\[ Y_{i,t} \sim \text{Pois} \left( \lambda_{i,t} \right) \]

\[ \lambda_{i,t} = \mu_{i,t} e^{\xi_i} \] (6)

\[ \mu_{i,t} = e^{\beta_0} f_t X_{i,t}^{1} X_{i,f}^{2} \] (7)

\[ Y_{i,t} \] = observed number of crashes at site \( i \) in year \( t \)

\[ \lambda_{i,t} \] = expected number of crashes at site \( i \) in year \( t \)

\[ \mu_{i,t} \] = expected number of crashes at sites similar to intersection \( i \) in year \( t \)

\[ X_{1,i,t} \] = AADT on major road at site \( i \) in year \( t \)

\[ X_{2,i,t} \] = AADT on minor road at site \( i \) in year \( t \)

\[ \beta_0 \] = Intercept term

\[ \beta_1, \beta_2 \] = Coefficients for \( X_{1,i,t} \) and \( X_{2,i,t} \) respectively

\[ f_t \] = Coefficient to account for time effects

For time trend model, \( f_t = \exp(\alpha t) \), where, \( \alpha \) is the coefficient for time \( t \) indicating expected crashes has an exponential smoothed trend. For time multiplier model, \( f_t = \exp(\alpha_t) \), where, \( \alpha_t \) is the coefficient varying across years similar to the annual factors in the EB method.

\[ e^{\xi_i} \] = random effects at site \( i \)

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Paper revised from original submittal.
There are at least two types of FB models based on the different functional form for the random effects $e^k_i$: Poisson Gamma (PG) models where $e^k_i \sim \text{gamma} (\varphi, 1/\varphi)$; Poisson Log Normal (PLN) models where, $e^k_i \sim \text{log normal} \ (0, \sigma^2)$, and $\sigma^2 \sim \text{Inverse Gamma} \ (0.001, 0.001)$. In this study, a log-linear form was assumed for the FB model (FB methods more easily allow the use of forms that are not log-linear, and examination of such models is a topic for future research).

7 Multivariate FB method

Multivariate FB methods explicitly account for the correlation between crash types that may be evaluated in a study. The multivariate Poisson Log normal (MVPLN) model approach has been introduced and applied to safety evaluations (19, 21).

In a multivariate model, crash counts $Y_{it} = (Y_{it}^1, Y_{it}^2, \ldots Y_{it}^L)$ can be described as $L$ types of multivariate crash records at location $i$ (where $i=1,2,\ldots,N$) in year $t$ ($t=1,2,\ldots,J$). Let $M$ be the number of covariates and $X=(1,X^1_1,X^2_2,\ldots X^M_M)'$, define $b^k=(b^k_0, b^k_1, b^k_2, \ldots b^k_M)'$ to be a $(K+1)$ dimensional regression coefficients for crash type $k$. Each type of crashes is assumed to be independently Poisson distributed.

$$ Y_{it}^k \sim \text{Poisson} (\lambda_{it}^k) $$

where:

$\lambda_{it}^k$ = the modified expected crashes of type $k$ at location $i$ in year $t$.

$\mu_{it}^k$ = the expected crashes of type $k$ at locations similar to location $i$ in year $t$, has the same form in Equation (9).

$\varepsilon_{it}^k$ = the multivariate random effect for crash type $k$ at location $i$.

The vector $\varepsilon_t=(\varepsilon_{1t}^1, \varepsilon_{1t}^2, \ldots \varepsilon_{1t}^L)$ is assumed to be multivariate normal distributed to account for the correlations among crashes of different types, that is: $\varepsilon_t \sim \text{N}_L(0, \Sigma)$.

$$ \Sigma = \begin{pmatrix}
    \sigma_{11} & \sigma_{12} & \ldots & \sigma_{1L} \\
    \sigma_{21} & \sigma_{22} & \ldots & \sigma_{2L} \\
    \vdots & \vdots & \ddots & \vdots \\
    \sigma_{L1} & \sigma_{L2} & \ldots & \sigma_{LL}
\end{pmatrix} \quad (10) $$

The MVPLN can be considered as an additive form of random effects that accounts for the extra-variation between sites with correlated random errors among crash types within a site. The correlation is unrestricted and can be positive or negative. Further, the univariate PLN can be seen as a special case of MVPLN when $\Sigma$ is a diagonal matrix. Both the MVPLN and univariate FB approaches use Markov Chain Monte Carlo (MCMC) (22, 23) methods to derive the posterior distribution of estimates.
Generally, the univariate FB model provides similar or slightly better results compared to the EB method (8). When crashes are correlated, the MVPLN model provides much better results compared to the univariate FB model and the EB method (10, 11, 21).

**Model Selection**

The objective in model selection is to use as parsimonious a model as possible while ensuring that reliable results are obtained. The deviance information criterion (DIC) includes a penalty for the complexity of the model. More information on the DIC can be found in Spiegelhalter et al. (7, 24).

**Applying the FB method**

Given the observed crash count $Y_{i,t}$ in the “after” period at treated site $i$, the intent is to compare this count with what level of safety $\lambda_{i,t}$ in the after period would have been expected had the treatment not been implemented. The procedure for predicting the expected number of crashes $\lambda_{i,t}$ in the after period without treatment includes two steps:

1. **Step 1:** Assuming $Y_{i,t} \sim \text{Poisson}(e^{x_i} \times \mu_{i,t})$, posterior distributions of the parameters are calibrated by Markov Chain Monte Carlo (MCMC) methods using the data from reference sites and the before period of treated sites.
2. **Step 2:** The corresponding expected total crashes $\lambda_{i,t}$ without treatment can then be obtained, given the traffic volumes at each treated site in the after period. The change in safety is the difference between the predicted $\lambda_{i,t}$ in the after period without treatment and the safety $Y_{i,t}$ in the same period with the treatment in place. The treatment effects can then be calculated, either in terms of a crash frequency change or in terms of a percentage change in crashes.

It should be noted, however, the FB method is an integrated procedure. Unlike the EB procedure, the FB model development and CRF calculation are done in one step.

**Crash Reduction Factor**

The crash reduction factor (CRF) can be calculated as follows:

Suppose $X_{i,t} \sim \text{Poisson}(\lambda_{i,t})$, $t = 1, 2, \ldots, t_{f} + 1, t_{f} + 2, \ldots t_{f} + t_{z}$

where:

- $t_{f}$ = the last year before treatment
- $t_{z}$ = the number of years after treatment
- $NT$ = total number of treated sites
- $Y_{i,t}$ = observed type $k$ crashes at location $i$ in year $t$
- $\lambda_{i,t}$ = expected crashes without treatment for intersection $i$ in year $t$ in the after period.
Crash Reduction Factor: \[ CRF = 1 - \frac{\sum_{i=1}^{NT} \sum_{t=t_i+1}^{t_{i+1}} Y_{i,t}}{\sum_{i=1}^{NT} \sum_{t=t_i+1}^{t_{i+1}} \tilde{Y}_{i,t}} \] (11)

2 DATA

The North Carolina Department of Transportation (NCDOT) provided data for 67 signalized intersections where LNF had been removed between 2001 and 2006 (these are the same sites that were used in an earlier evaluation by Murphy (5)). In addition, data were also available for 395 intersections that remained on LNF operation from 2000 to 2007. NCDOT staff extracted crash data by crash type and severity from years 2000 to 2007 for treatment and reference groups from the Traffic Engineering Accident Analysis System (TEAAS). Each crash that occurred at the treatment sites was examined closely by NCDOT staff to ensure that they were accurately coded. AADT data were extracted from AADT maps by NCDOT staff. NCDOT also provided information on the number of legs and area type (rural versus urban). In addition, HSRC staff carefully used Google maps to verify the number of leg for all the treatment and reference sites.

Three intersections that were on freeway ramps were excluded because AADT data were not available for at least one of the legs. In addition, three other treatment sites were also excluded because the treatment was implemented in 2007 and NCDOT did not provide crash data for subsequent years. Finally, 61 treatment sites were used for further study. Two reference groups were available: one operating LNF from 11:00 pm to 6 am, another group from midnight to 6 am (see Table 1). Data for the 61 treated and 395 reference sites are summarized in Tables 2 and 3.

<table>
<thead>
<tr>
<th>Treatment Group</th>
<th>Number of sites</th>
<th>LNF operating time before removal</th>
<th>Reference Group</th>
<th>Number of sites</th>
<th>LNF operating time during the study period</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>23:00-6:00</td>
<td>Group1: 329 sites Group 2: 66 sites</td>
<td>Group1: 329 sites</td>
<td>23:00-6:00</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0:00-6:00</td>
<td></td>
<td>23:00-6:00</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>23:00-5:30</td>
<td></td>
<td>0:00-6:00</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>23:00-5:00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0:00-5:00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>0:00-5:30</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>21:10-6:20</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>23:40-6:00</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Total crashes, injury and fatal crashes, and frontal impact crashes in LNF periods were investigated as part of the evaluation. Summary data for treatment and reference groups are shown in Tables 2 and 3, respectively. NCDOT indicated that there were at least two possible
reasons for removing LNF: (1) policy decision – here a jurisdiction decides to remove LNF as a policy, (2) crash history during the LNF operation.

It is important to note that night time traffic volume was not available for the study. This is obviously a limitation. Further research could examine the effect of night time traffic volume to see if that has any effect of the crash impacts.

Table 2  Summary data for 61 treated intersections

<table>
<thead>
<tr>
<th>Variable</th>
<th>Mean</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Years before</td>
<td>4.46</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>Years after</td>
<td>2.13</td>
<td>0.58</td>
<td>4.58</td>
</tr>
<tr>
<td>Total LNF Crashes/site-year before</td>
<td>1.77</td>
<td>0.00</td>
<td>6.75</td>
</tr>
<tr>
<td>Total LNF Crashes/site-year after</td>
<td>0.66</td>
<td>0.00</td>
<td>3.75</td>
</tr>
<tr>
<td>Injury &amp; Fatal LNF Crashes/site-year before</td>
<td>1.05</td>
<td>0.00</td>
<td>4.75</td>
</tr>
<tr>
<td>Injury &amp; Fatal Crashes/site-year after</td>
<td>0.30</td>
<td>0.00</td>
<td>2.25</td>
</tr>
<tr>
<td>Frontal Impact LNF Crashes/site-year before</td>
<td>1.40</td>
<td>0.00</td>
<td>6.50</td>
</tr>
<tr>
<td>Frontal Impact LNF Crashes/site-year after</td>
<td>0.35</td>
<td>0.00</td>
<td>3.00</td>
</tr>
<tr>
<td>Major road AADT before</td>
<td>22103</td>
<td>2550</td>
<td>59000</td>
</tr>
<tr>
<td>Major road AADT after</td>
<td>21281</td>
<td>3000</td>
<td>48500</td>
</tr>
<tr>
<td>Minor road AADT before</td>
<td>7941</td>
<td>1000</td>
<td>22375</td>
</tr>
<tr>
<td>Minor road AADT after</td>
<td>7983</td>
<td>1000</td>
<td>23333</td>
</tr>
</tbody>
</table>

Table 3  Summary data for 329 reference intersections

<table>
<thead>
<tr>
<th>Variable</th>
<th>Mean</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Years</td>
<td>8</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>Total LNF Crashes/site-year</td>
<td>0.15</td>
<td>0</td>
<td>4</td>
</tr>
<tr>
<td>Injured LNF Crashes/site-year</td>
<td>0.06</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>Frontal Impact LNF Crashes/site-year</td>
<td>0.07</td>
<td>0</td>
<td>4</td>
</tr>
<tr>
<td>Major road AADT</td>
<td>13078</td>
<td>1900</td>
<td>57750</td>
</tr>
<tr>
<td>Minor road AADT</td>
<td>3183</td>
<td>210</td>
<td>28000</td>
</tr>
</tbody>
</table>

IMPLEMENTATION OF THE EB METHOD

As discussed earlier, the EB method can be divided into 3 steps: developing reliable SPFs, combining SPF estimates with observed crashes to obtain estimates of crashes in the after period without treatment, and calculating CRFs. For this specific dataset, the unique SPF development and modification technique to address data uncertainty is enunciated below:
SPF Development

Since night time traffic volumes were not available and the number of crashes at night in the reference group was minimal, SPFs were estimated using 24 hour crash data for total, injury and fatal, and frontal impact crashes using reference group 1 which operated LNF from 23:00 to 6:00. The sample size for reference group 2 was too small (66 sites) to estimate reliable SPFs. In addition to the traffic volume, indicator variables corresponding to area type (rural/urban), number of legs (3 leg/4 leg), and route type (US route, NC route, or other), were included in the models to develop SPFs.

The final SPFs for total, injury and fatal crashes, and frontal impact crashes are:

Total Crashes:

\[ E(tot) = \exp(\alpha_{US,NC}) \cdot e^{-7.2485} \cdot X1^{0.7212} \cdot X2^{0.1956} \]  \hspace{1cm} (12)

Where,

- \( E(tot) \) = expected total crashes during 24 hour period
- \( \alpha_{US,NC} = 0 \), if any street is US or NC route at the intersection; 0.2205, otherwise.
- \( X1 = \text{AADT on major street} \)
- \( X2 = \text{AADT on minor street} \)

Scaled Pearson \( \chi^2 \) divided by degrees of freedom = 1.054

Injury and Fatal Crashes:

\[ E(inj) = \exp(\beta_{US,NC}) \cdot e^{-8.2004} \cdot X1^{0.7277} \cdot X2^{0.1896} \]  \hspace{1cm} (13)

Where,

- \( E(inj) \) = expected 24 hour injury and fatal crashes
- \( \beta_{US,NC} = 0 \), if any street is US or NC route at the intersection; 0.186, otherwise.

Scaled Pearson \( \chi^2 \) divided by degrees of freedom = 1.051

Frontal Impact Crashes:

\[ E(frt) = \exp(\gamma_{US,NC}) \cdot \exp(\gamma_{3A}) \cdot e^{-7.874} \cdot X1^{0.6944} \cdot X2^{0.2121} \]  \hspace{1cm} (14)

Where,

- \( E(frt) \) = expected 24 hour frontal impact crashes
- \( \gamma_{US,NC} = 0 \), if any street is US or NC routes at the intersection; 0.2567, otherwise.
- \( \gamma_{3A} = 0 \), if it is a 4 legged intersection; -0.2254, if it is a 3 legged intersection

Scaled Pearson \( \chi^2 \) divided by degrees of freedom = 1.163

Area type (rural/urban) was not statistically significant in any of three SPFs, and the number of legs was not statistically significant (at the 0.05 level) in the SPFs of total and injury and fatal crashes. The developed SPFs were applied to reference group 1 to obtain annual factors, which are computed by taking the ratio of observed crashes to SPF predictions in each year in the reference group 1.
Factors to Recalibrate SPF for LNF Crash Estimation

In addition to the annual calibration factors, additional factors are necessary to estimate the predicted number of crashes during the LNF period at the treatment sites. These additional factors were multiplied with the predictions from the SPF to estimate the predicted values for use in the empirical Bayes analysis.

The first factor is the proportion of crashes at night in the reference group. Ideally this factor needs to be calculated for each LNF treatment group based on a reference group with similar LNF time periods. However, the data includes only two reference groups: group 1 having LNF from 23:00 to 6:00 and reference group 2 operating LNF between 0:00 and 6:00.

Table 4: Proportion of LNF crashes (LNF/all day) from reference group (Factor 1)

<table>
<thead>
<tr>
<th>LNF</th>
<th>Total</th>
<th>Injury &amp; Fatal</th>
<th>Frontal impact</th>
<th>Calculated from</th>
<th>Applied to</th>
</tr>
</thead>
<tbody>
<tr>
<td>0:00-6:00</td>
<td>0.0552</td>
<td>0.0643</td>
<td>0.0541</td>
<td>Reference group 2</td>
<td>0:00-6:00</td>
</tr>
<tr>
<td>23:00-6:00</td>
<td>0.0478</td>
<td>0.0478</td>
<td>0.0507</td>
<td>Reference group 1</td>
<td>all others</td>
</tr>
</tbody>
</table>

The second factor was to account for the fact there was not always a one to one correspondence between the LNF time period in the treatment group before LNF removal and the LNF period in the reference group 1. Factor 2 was estimated by taking the ratio of the number of crashes during each LNF period for a particular group of treatment sites divided by the number of crashes during 23:00-6:00, which is the LNF time period for reference group 1 (see Table 5).

Table 5: Second factor (factor 2) to account for differences in the LNF time periods between treatment and reference sites

<table>
<thead>
<tr>
<th>LNF</th>
<th>Total</th>
<th>Injury and fatal crashes</th>
<th>Frontal impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>23:00-6:00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>23:00-5:30</td>
<td>0.89</td>
<td>0.87</td>
<td>0.85</td>
</tr>
<tr>
<td>23:00-5:00</td>
<td>0.84</td>
<td>0.79</td>
<td>0.77</td>
</tr>
<tr>
<td>21:10-6:20</td>
<td>1.79</td>
<td>1.88</td>
<td>1.84</td>
</tr>
<tr>
<td>23:40-6:00</td>
<td>0.83</td>
<td>0.80</td>
<td>0.75</td>
</tr>
<tr>
<td>0:00-6:00</td>
<td>0.72</td>
<td>0.71</td>
<td>0.64</td>
</tr>
<tr>
<td>0:00-5:30</td>
<td>0.61</td>
<td>0.58</td>
<td>0.49</td>
</tr>
<tr>
<td>0:00-5:00</td>
<td>0.56</td>
<td>0.50</td>
<td>0.41</td>
</tr>
</tbody>
</table>

As shown in Tables 2 and 3, the LNF crashes in the treatment group are much higher than those in reference group (here, reference group implies reference group 1, the group that was

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Paper revised from original submittal.
used in estimating the SPF\(s\)). Further investigation revealed that the proportion of crashes at night in the before period of treatment group was significantly higher than the reference group. While it is possible that some of this difference may be due to RTM, it is most likely that a significant portion of this difference is due to factors that could be not explicitly considered in this analysis, e.g., differences in night time traffic volume between the treatment and reference groups. Hence, another factor was applied: factor 3 is the ratio of proportion of crashes at night in the before period of treatment group to the reference group. It was calculated using Equation 15. Factor 3 was 3.194, 4.703 and 4.714 for total, injury and fatal crashes, and frontal impact crashes respectively.

\[
\text{Factor 3} = \frac{\left(\frac{\text{Crashes in LNF}}{\text{Crashes in 24 hours}}\right)}{\left(\frac{\text{Crashes in LNF}}{\text{Crashes in 24 hours}}\right)}_{\text{reference group}}
\]  

(15)

EB Results

The final crash reduction factors (CRFs) along with the standard errors (in brackets) for total, injury and fatal, and frontal impact crashes as a result of the LNF removal were as follows:

- Total crashes: 40\% (7\%)
- Injury and fatal crashes: 42\% (9\%)
- Frontal impact: 46\% (8\%)

IMPLEMENTATION OF THE FB METHOD

The FB method was applied to 57 treatment sites: 4 treatment sites had to be removed because of missing data in certain years for 4 of the treatment sites – FB MVPLN methods cannot be implemented unless all years of data are available for a particular treatment site.

Univariate FB method

Since there are 8 LNF periods in the treatment group as seen in Table 1, a factor \(\beta_k\) in Equations 16 and 17 was applied to allow for the differences among the different LNF treatment sites. Poisson gamma (PG) and Poisson Lognormal (PLN) models with two time effects functions (time trend and time multiplier models), were explored. The logarithm function form of \(\mu_{t,i}\) is shown below:

Time multiplier model:

\[
\ln(\mu_{t,i}) = \beta_k + \beta_0 + \alpha t + \beta_1 \ln(X_{1i,t}) + \beta_2 \ln(X_{2i,t}) + \alpha_1 X_{U5,NC} + \alpha_2 X_{3,4} + \alpha_3 X_{U,R}
\]  

(16)

Time trend model:

\[
\ln(\mu_{t,i}) = \beta_k + \beta_0 + \alpha t + \beta_1 \ln(X_{1i,t}) + \beta_2 \ln(X_{2i,t}) + \alpha_1 X_{U5,NC} + \alpha_2 X_{3,4} + \alpha_3 X_{U,R}
\]  

(17)
where:
\[ \mu_{i,t} = \text{expected number of crashes at sites similar to intersection } i \text{ in year } t \]
\[ X_{1,i,t} = \text{AADT on major road at site } i \text{ in year } t \]
\[ X_{2,i,t} = \text{AADT on minor road at site } i \text{ in year } t \]
\[ X_{US,NC} = \text{Dummy variable; } X_{US,NC} = 1, \text{ if any street at the intersection is US or NC route; } X_{US,NC} = 0 \text{ otherwise} \]
\[ X_{3,4} = \text{Dummy variable; } X_{3,4} = 1 \text{ for 4 legged intersection, 0 otherwise} \]
\[ X_{U,R} = \text{Dummy variable; 1 for urban intersection, 0 otherwise} \]
\[ \beta_0, \beta_1, \beta_2, \alpha_1, \alpha_2, \alpha_3 = \text{Coefficients} \]
\[ \alpha = \text{Coefficient for time } t \text{ indicating expected crashes has an exponential smoothed trend (in the time trend model)} \]
\[ \alpha_k = \text{Coefficient varying across years similar to the annual factor in the EB method} \]
\[ \beta_k = \text{Random coefficients allowing variation among the different LNF periods,} \]
\[ k=1, 2, \ldots, 8 \]

As discussed earlier, the FB method has more flexibility to choose the functional form of \( \mu_{i,t} \). Usually, the number of legs and rural/urban are significant factors in the model function form (SPFs for the EB method). However, in the SPFs that were estimated for the EB analysis, these variables were not always statistically significant and hence not included. In the FB method, even parameters that are not statistically significant can be included and explored.

**Multivariate FB method**

The multivariate FB was examined to address the possible correlation between the 3 crash types: total, injury and fatal, and frontal impact. The logarithm function form of \( \mu_{i,t} \) was the same as Equations 16 and 17. The random errors among the three crash types studied were assumed to follow multivariate log normal distribution (as mentioned earlier).

**Model selection**

The FB models were calibrated in WinBUGS. Two parallel chains were run to obtain posterior distributions of the coefficients and crash reduction factor estimates. Convergence was monitored by Gelman-Rubin convergence diagnostic plots and historical plots set in WinBUGs (7). DICs were calculated for all following six models:

- Univariate: PG with time trend
- Univariate: PG with time multiplier
- Univariate: PLN with time trend
- Univariate: PLN with time multiplier
- Multivariate: PLN with time trend
- Multivariate: PLN with time multiplier
PG with time multiplier model was the best among the 4 univariate FB models and MVPLN with time multiplier model was better than the time trend model based on the DIC value. Since FB models are able to include statistically insignificant covariates for the estimation of CRFs, DICs were compared by including and excluding statistically insignificant variables (if any), for the two time multiplier models respectively. DICs were 6773 and 6392 for the best univariate PG and MVPLN time multiplier models respectively. Much lower DIC of the MVPLN time multiplier model implies that this model is better than the univariate model, indicating the total, injury and fatal, and frontal impact crashes in LNF period are correlated. The observed crash records of total, injured, and frontal impact crashes in LNF periods were further examined and the covariance and correlation matrix among the three types of crashes are shown in Table 6. It is clear that the three types of crashes are indeed strongly correlated. Both results indicate that a multivariate approach, rather than a univariate method, should be employed to estimate CRFs. The results from the best univariate FB model (PG time multiplier) and from the recommended MVPLN time multiplier model are illustrated in Table 7.

Table 6 Correlation and Covariance matrixes

<table>
<thead>
<tr>
<th>Correlation matrix</th>
<th>Injury &amp; fatal</th>
<th>Frontal impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>total</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Injury &amp; fatal</td>
<td>0.807</td>
<td>1</td>
</tr>
<tr>
<td>frontal impact</td>
<td>0.789</td>
<td>0.751</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Covariance matrix</th>
<th>injured</th>
<th>Frontal impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>total</td>
<td>2.953</td>
<td></td>
</tr>
<tr>
<td>injured</td>
<td>1.310</td>
<td>0.894</td>
</tr>
<tr>
<td>frontal impact</td>
<td>1.570</td>
<td>0.822</td>
</tr>
</tbody>
</table>

Table 7 LNF Crash reduction factors (FB method)

<table>
<thead>
<tr>
<th></th>
<th>Univariate</th>
<th>Multivariate</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Poisson_Gamma</td>
<td>Poisson_Log_Normal</td>
</tr>
<tr>
<td>DIC</td>
<td>6773</td>
<td>6392</td>
</tr>
<tr>
<td>CRF</td>
<td>Std. of CRF</td>
<td>CRF</td>
</tr>
<tr>
<td>Total Crashes</td>
<td>40%</td>
<td>7%</td>
</tr>
<tr>
<td>Injury &amp; Fatal</td>
<td>39%</td>
<td>11%</td>
</tr>
<tr>
<td>Frontal Impact Crashes</td>
<td>48%</td>
<td>8%</td>
</tr>
</tbody>
</table>

The CRFs from the MVPLN are higher indicating that the univariate methods underestimate the safety effects for this particular evaluation. The corresponding standard
deviation (Std.) is lower than those from the univariate model. The lower standard deviation values indicate MVPLN can provide more stable results.

3 DISCUSSION AND CONCLUSION

As discussed earlier, the previous studies on LNF removal have used a variety of methods including naïve before-after, univariate before-after EB, and before-after EB using the method of sample moments (without traffic volumes). All of them concluded that removing LNF reduced crashes, although the magnitude of the reduction varied among the studies. Some of the studies used very limited sample sizes. This effort employed the before-after EB, the univariate FB, and the multivariate FB method (to address the correlation among the crash types), to evaluate the treatment effect using a relative large sample of treatment sites (67 sites). The analysis undertaken examined the safety impacts of converting LNF to normal phasing operation at signalized intersections. In order to directly compare the results from the EB and FB methods, the EB method was repeated using the 57 treatment sites that were used in the FB evaluation. The results from the naïve, EB, FB (univariate PG), and FB (MVPLN) time multiplier models are shown in Table 8.

Table 8 Comparison of Naïve, EB and FB (LNF period)

<table>
<thead>
<tr>
<th>Method</th>
<th>EB Before-After</th>
<th>FB Before-After</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Univariate</td>
<td>MVPLN</td>
</tr>
<tr>
<td></td>
<td>Poisson-Gamma</td>
<td>Poisson-Log Normal</td>
</tr>
<tr>
<td></td>
<td>DIC=6773</td>
<td>DIC=6392</td>
</tr>
<tr>
<td>CRF</td>
<td>CRF</td>
<td>CRF</td>
</tr>
<tr>
<td></td>
<td>Std. of CRF</td>
<td>Std. of CRF</td>
</tr>
<tr>
<td>Total</td>
<td>63%</td>
<td>40%</td>
</tr>
<tr>
<td>Injury &amp; Fatal</td>
<td>71%</td>
<td>41%</td>
</tr>
<tr>
<td>Frontal Impact</td>
<td>74%</td>
<td>48%</td>
</tr>
</tbody>
</table>

It can be seen the results from the EB method are almost identical to the univariate FB. The EB method, however, required data on 24 hour crashes for estimating SPFs, reference group 2 (to calculate the appropriate portion of LNF crashes), and a few additional factors for the evaluation. The FB method (univariate FB or multivariate FB), on the other hand, did not need such information. The naïve method overestimated the treatment effects, possibly due to RTM. Moreover, the FB method offers more flexibility in selecting the functional form of $\mu_{it}$ (similar to SPF in the EB), and the ability to address uncertainty in the data. Compared to the univariate FB, the MVPLN provide better results based on much lower DIC values. Furthermore, the strong correlation among the three types of crashes also indicates that a multivariate approach is more appropriate. For this particular data set, the MVPLN multiplier time model was favored and the recommended CRFs are 48% (±6%), 53% (±8%), and 57% (±7%) for nighttime total, injury and fatal, and frontal impact crashes, respectively.
Future research could investigate the conditions under which removing LNF may be more or less beneficial, and possibly develop crash modification or reduction functions. Data on night time traffic volumes would help in this endeavor.

4 ACKNOWLEDGMENTS

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REFERENCES


