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# Policy considerations for evaluating the safety effectiveness of passing lanes on rural two-lane highways with lower traffic volumes: Wyoming 59 case study

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## ABSTRACT

Transportation agencies across the nation are continuously evaluating the safety and operation of their rural two-lane highways. The three most common countermeasures are to do nothing, add passing lanes to target sections, or to upgrade to four-lane. The goal of this article is to update the current body of knowledge available to agencies on the process of implementing countermeasures and realistically evaluating their safety effectiveness. The Wyoming Department of Transportation (WYDOT) constructed nine passing-lane segments on a 26-mile stretch of rural two-lane highway. Preliminary analysis using 7-year crash data showed that the safety benefit was negligible at best. However, utilizing Empirical Bayes and Wyoming-specific safety performance functions, it was shown that the basic approach of comparing crash rates underestimated fatal and injury (F+I), and lane-departure crashes and that the passing lanes had a significant safety benefit. Furthermore, the authors looked at what would have happened from a safety and cost perspective had no countermeasure been implemented and then also if the road had been upgraded to four-lane undivided instead of just adding passing lanes. It was shown that passing lanes are the best option from a safety and cost perspective especially when agencies have constrained budgets.

## KEYWORDS

safety effectiveness; crash modification factors; *Highway Safety Manual*; passing lanes; two-lane roadways; Empirical Bayes

## 1. Introduction

Two-lane highways offer a single lane for each direction of travel. Therefore, opposing traffic characteristics affect roadway performance and operation. High-traffic volumes and percentage of trucks limit the opportunities for passing because the passing vehicle must occupy the opposing lane to complete the maneuver. Roadway geometrics and terrain type further limit passing due to sight-distance restrictions. Addressing the safety of upgrading two-lane roadways is a vital step toward achieving the overall goal of the American Association of State Highway

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Transportation Officials (AASHTO) strategic highway safety plan of reducing fatalities on the U.S. roads (AASHTO, 2005). Transportation agencies use standard practices from the *Highway Capacity Manual* (Transportation Research Board, National Research Council, 2010) and AASHTO (2011) green book to monitor these factors and to collect data on average travel speed, percent time spent following, directional distribution, and collisions to determine when to implement passing countermeasures. Countermeasures can include changing geometrics to increase sight distance to allow more opportunities to pass in the opposing lane, creating passing lane segments in target areas or upgrading to a four-lane highway. Due to budgetary constraints and relative safety effectiveness, implementing passing lane segments is a commonly chosen countermeasure (Wolldridge et al., 2001). Passing lanes improve the safety, operation, and mobility by breaking up platoons and reducing delays from following slower moving vehicles.

There are several possible arrangements for constructing passing lanes including separated intermittent, tail-to-tail, head-to-head, intermittent overlapping, continuous passing, and finally short four-lane sections. In general, as the frequency of passing lanes increases the level of service also increases. One study showed that the nonintersection crash frequency per-mile per-year within passing lanes was 12% to 24% lower than for regular two-lane highway sections (Potts & Harwood, 2004). As average annual daily traffic (AADT) increases, the range of benefit is larger (Harwood & St. John, 1985).

After agencies implement passing lanes on a two-lane highway, they need to evaluate the safety benefit of the countermeasure. A common approach is to conduct a before/after (B/A) safety effectiveness evaluation, but this is often difficult to complete properly, because the Empirical Bayes (EB) method (Hauer, 1997) involves 14 rigorous and time-consuming steps and requires properly calibrated safety performance functions (SPFs). To obtain an answer with available resources, many agencies will resort to performing a simple B/A observational study, based on crash data and traffic volumes to make a judgment on the improvement. This approach can lead the agency and public to believe that a countermeasure is more or less effective than it actually is. This is due to the fact that there is no correction for regression-to-the-mean bias (RTM) and no consideration taken into the conditions specific to the highway such as weather, driver population, animal behavior, oversized truck traffic, and other sundry factors. However, these and other site-specific influences can be taken into consideration with calibrated SPFs and the EB analysis outlined in the *Highway Safety Manual (HSM)* (AASHTO, 2010). The HSM also provides a base crash modification factor (CMF) of 0.75 for the implementation of passing lanes on two-lane highways (AASHTO, 2010).

The WYDOT recently implemented passing lanes on several two-lane highways that were underperforming based on traffic and safety characteristics. Construction of passing lanes is one of the most common and cost-effective practices to improve traffic safety and mobility on rural two-way roadways

(Wolldridge et al. 2001). However, even though this is a very common countermeasure there have been very few studies and updates to policy to properly evaluate the safety benefits of this countermeasure. There are many ways to evaluate safety effectiveness; but to do it properly, there has to be a statistical analysis performed that corrects for RTM bias and considers site-specific characteristics. Simply comparing crash rates does neither of these things. Many transportation agencies evaluate safety effectiveness by crash rates that are only based on traffic volumes and crash counts. A review of the literature showed that conclusions were often made on safety effectiveness, even though those conclusions relied on basic crash rate comparisons. For example, a document published in 2004 concluded that passing lane installation reduced accident rates by 25% (Potts & Harwood, 2004), but again this conclusion was based on crash counts and traffic volume data. Another study, published in 2002 showed that passing lanes reduce total crashes by 25% and (Fatal+Injury, or F+I) crashes by 30% that were also found by crash rate comparisons (Fitzpatrick, Parham, & Brewer, 2002). On the other hand, a good example of a complete safety effectiveness evaluation was completed for Michigan where the authors used EB and cross-sectional analysis to accurately evaluate passing lane additions (Persaud, Lyon, Bagdade, & Ceifetz, 2013). As stated previously, an update to policy is needed so that safety effectiveness of countermeasures can be completed accurately.

Simple B/A evaluations often provide poor conclusions on safety effectiveness due to circumstances unique to the area. For example, Wyoming is distinctive due to its severe weather, oil, gas, and mining industry-related traffic and also because it is home to some of the leading migratory populations of big game animals in the United States (Sawyer, Lindzey, & McWhirter, 2005) that lead to high amounts of animal-related collisions. These unique attributes make it difficult to evaluate safety performance without calibrated SPFs.

Various observational before-after analyses were utilized in this study to explore the relationship between the number of lanes, severity of crashes, and target crash types, these methodologies ranged from simple (naïve) before-after to the more complex EB. The EB method required calibrated SPFs that were designed specifically for rural low-volume two-lane highways in Wyoming. Due to the nature of the roadway, the immediate need for a safety evaluation and the fact that many transportation agencies (including Wyoming) currently only have access to simple SPFs, a negative binomial model was calibrated using AADT-based SPFs only. Although full SPFs are preferable to simple SPFs, it is unrealistic to expect all transportation agencies to have site-specific full SPFs especially when considering constrained budgets, low-traffic volumes, and unique attributes of roadway sections. Policy should advise that when full SPFs are unavailable, simple site-specific SPFs are the next best option.

The following sections illustrate the procedures of preparing the data, statistical methodologies, results and discussion, and the conclusions.

## 2. Data description and preparation

Observational before-after studies are the most common and accepted approach used for safety effectiveness evaluations. It should be noted that the more complex varieties of these evaluation methods are very data intensive; the assessment is more in depth than comparing before and after crash data at treatment sites because consideration also is given to changes in traffic and other sundry factors.

Between 2005 and 2006, the WYDOT constructed nine passing lanes on a 26-mile section of WY59, a rural two-lane highway between Douglas and Gillette, Wyoming. The study section of WY59 has mixed-use traffic from local, recreational, and energy users. Recreational traffic is generated from visitors to Thunder Basin National Grassland and the Belle Fourche River. The area has heavy use from the energy industry including several coal mines and gas power plants that generate high truck volumes including oversized heavy vehicles.

In total, the construction project added 10.03 miles of passing lanes. Crash data for the section was collected from WYDOT's C9 system from 1997 to 2004 and 2007 to 2013. Crashes occurring in 2005 and 2006 were omitted due to construction of passing lanes. The study period included a total of 8 years in the before period, 2 years removed for construction, and 7 years in the after period. This amounts to a study period spanning approximately 17 years that can lead to various changes in facility characteristics. For this reason, though more crash data is available in the before period it is not advantageous to use. There is a fine balance between having enough data in the before and after period to limit RTM bias while also keeping the effects on crash data from changes in facility characteristics over time to an acceptable minimum.

Crashes involving driver impairment, intersections, and animals were removed because they have diminutive correlation to evaluating passing lane effectiveness. The main types of driver-impaired crashes that were not considered involved alcohol or drug abuse and drivers that were fatigued or emotionally distressed. Crashes that involved intersection-turning movements were also removed because these are not directly correlated to passing lane safety effectiveness and that low-volume roads intersecting highways can be considered insignificant (Mutabazi, Russell, & Stokes, 1999).

There are approximately 1.5 million large animal vehicle collisions that occur in the United States every year (Sawyer et al., 2005). For Wyoming two-lane undivided highways the statewide average is more than 36% for wild animal collisions (Kononov & Allery, 2010). The project had a close proximity to wildlife habitat, and as a result there were 106 reported crashes involving animals during the study period. However, the actual number of crashes was most likely higher because in the 5-year period from 2007 to 2011 WYDOT's carcass count was close to 500, but the reported crash count was only 59. This indicates a high level of unreported animal-related

collisions. Although animal crashes were not considered for this study, this information highlights the need to use calibrated SPFs when considering safety effectiveness. Further research is needed to analyze the effects of animal collisions on SPFs.

This study focused on CMFs based on severity (F+I) and total crashes and lane-departure crashes for each passing lane location. These CMFs for passing segments were then compared to CMFs for the entire study area. The entire study area was broken into four segments based on the AADT data. The four segments were then used to develop the CMFs for the entire study area. Due to the low volumes of traffic and relatively low crash counts, there was a lot of unusable data when calculating crash rates that lead to a high amount of standard error. This problem is common while analyzing data from low volume roads. For example, Mutabazi et al. (1999) conducted a myriad number of passing lane studies. One study in particular found that “accident data were insufficient to detect any significant difference in any accidents before and after the construction of passing lanes” (Mutabazi et al., 1999, p. 183). The advantage of using an EB approach is that it can use the expected crash rate in places with no crash data due to the low traffic volumes that in turn leads to more reliable results. EB is recognized as the most reliable method for creating CMFs (Gross, Persaud, & Lyon, 2010). This further proves the need for a policy change to only accept non-naïve safety effectiveness evaluations.

Two sets of data were used in this study: (1) information from the sites where treatment (conversion from two-lane roadway to two-lane with passing lanes) was applied and (2) information from the entire corridor. Various information including as-built plans, site geometrics, and construction costs were collected from WYDOT for the passing lane project on WY59. Additionally, WYDOT provided Wyoming specific SPFs (Kononov & Allery, 2010), carcass counts (WYDOT, 2013), traffic characteristics, updated societal cost factors, and raw crash data. For each of the nine passing lane segments in the study area, the collected information included start construction date, end date, roadway ID, beginning mile post, ending mile post, and additional traffic, driver and roadway characteristics data. Google Earth was also utilized to verify the treated sites and their accurate start and end dates. Table 1, presents an overall summary for the conversion of the two-lane highway to two-lane highway with passing lanes. The 26-mile study area consisted of nine passing lane segments that totaled approximately 10 miles. The entire study

**Table 1.** Summary of the conversion of two-lane to two-lane with passing lanes data.

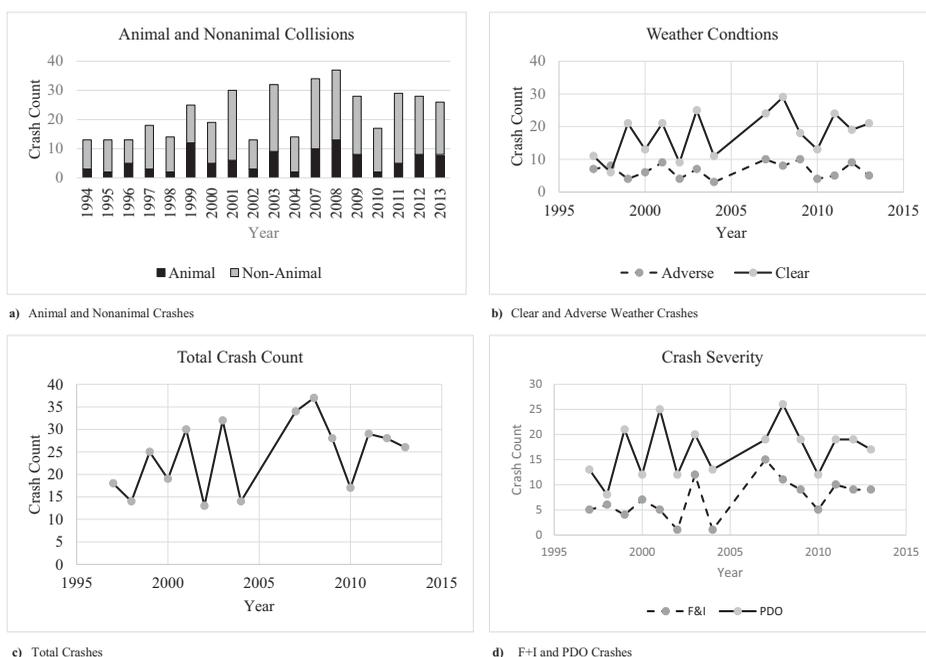
Segment Type	Number of Segments	Average Segments Length (mile)	Total Length (mile)
Passing lane	9	1.1	10.03
Whole corridor	4	6.5	26

area was also separated into four segments based on AADT. This approach similar to those used in research done by Kansas State University (Mutabazi et al., 1999).

The crash data for the aforementioned treated segments during the before (8 years before construction start date) and after periods (7 years after the construction end date) were collected from WYDOT's Critical Analysis Reporting Environment (CARE) system. The geometric characteristics were obtained from as built plans and the traffic volumes (AADT) were gathered from WYDOT's 2013 *Vehicle Miles Book* ([http://www.dot.state.wy.us/home/planning\\_projects/Traffic\\_Data.default.html](http://www.dot.state.wy.us/home/planning_projects/Traffic_Data.default.html)). The crash data was segregated into four types; total number of crashes, and severe crashes (F+I) for the whole study area and then total number of crashes and severe crashes for each of the nine passing lane segments. Additionally, crash data was isolated into target crash types by investigating the manner of collision including head on, roll-over, run-off-road, and side swipe collisions. There was a general trend of crash reduction after the conversion of two-lane to two-lane with passing lanes in the segments with passing lanes. However, the results were less clear when the entire study area was considered. The average crash rate per year per million vehicle miles traveled (MVMT) was 0.86 for the treated sections in the before period and 0.48 in the after period. For the entire study area the crash rate was observed to be 0.42 in the before and 0.33 in the after period.

### 3. Preliminary analysis

When a transportation agency is evaluating the safety effectiveness of a countermeasure, it is important for them to analyze the unique attributes of the road. For



**Figure 1.** Yearly crash trends. F+I = Fatal+Injury; PDO = Property damage only.

example, the section of road in Wyoming that was analyzed had a high number of animal- and weather-related collisions as can be seen in Figures 1a and 1b. Although animal- and weather-related crashes were not considered in the safety effectiveness evaluation they highlight the need for calibrated SPFs in evaluations.

Trends in crash severity were also analyzed as part of the preliminary analysis. Figures 1c and 1d show that the overall changes in crash severity and total crashes have a high probability for RTM bias and the necessity for EB analysis for safety effectiveness evaluations. Based on the preliminary analysis, it is easy to conclude that for this study section it is statistically probable that a period of high crash counts will be followed by a period of low crash counts regardless of countermeasures and treatments. If a countermeasure is applied between two periods, it can cause the results of the safety effectiveness evaluation to appear over- or underinflated.

Due to the low crash frequency, low traffic volumes, and small number of crashes for each type on Wyoming two-lane roadways, the results had very high standard error and yielded statistically insignificant results that are summarized in Table 2. Inclinations in the variation of crash severity also highlight the need for site specific-calibrated SPFs provided in Table 3. For this reason, the crash types were consolidated into total, F+I, and lane-departure collisions for the EB analysis. The lane-departure crashes included head-on collisions, rollover, run off road, and side swipe opposite collisions. Side swipe same-direction collisions were purposefully left out of the lane-departure crash group because these collisions have a known association to passing maneuvers.

#### 4. Method

CMFs express the safety consequences of some treatment or intervention that has been implemented on a roadway facility. As mentioned earlier, one of the

**Table 2.** Preliminary crash modification factors (CMFs) by collision type.

Collision Type	Whole Corridor		Passing Lane Segments	
	CMF (Safety Effectiveness)	S.E.	CMF (Safety Effectiveness)	S.E.
Head on	2.24 (123.69%)	0.08 7.998	0.49 (-50.64%)	0.35 34.904
Rear end	0.38 (-62.12%)	0.35 34.811	0.24 (-75.89%)	0.10 10.126
Rollover	1.31 (31.00%)	0.09 8.533	0.72 (-27.91%)	0.08 7.565
Run off road	0.71 (-29.39%)	0.08 7.743	1.14 (14.03%)	0.22 22.270
SS opposite	1.11 (-10.82%)	0.21 20.823	0.67 (-33.25%)	0.32 31.947
SS same	0.53 (-46.88%)	0.06 6.399	0.49 (-50.93%)	—
Total	0.79 (-20.79%)	0.11 11.291	0.94 (-5.57%)	0.06 5.852

(-) Correspond to Safety Effectiveness – Limitation in Crash Data; SS = sideswipe.

**Table 3.** Wyoming-specific SPFs for rural flat and rolling two-lane roads (total and F+I crashes).

Crash Severity	Wyoming-Specific SPFs		
	Intercept Estimate	Log (AADT) Estimate	Dispersion(k)
Total	-6.4633	0.8220	0.2242
F+I	-7.3609	0.7700	0.2235

AADT = Annual average daily traffic; SPF = safety performance function; F+I = Fatal+Injury.

main methodologies to examine the effect of highway and traffic engineering measures on safety is the “observational study.” The “observational before-after” study is more advantageous over other types because it can capture the safety implications of a certain improvement or operational change where many of the attributes (e.g., geometry and other site characteristics) of a study facility remain unchanged. For example, the evaluation of the safety effect associated with installing a passing lane falls under the “observational before-after” study category (Persaud et al., 2013).

#### 4.1. Naïve before-after

The naïve before-after (B/A) approach is the simplest approach and is often used by transportation agencies to quickly deduce the performance of a countermeasure. Crash counts in the before period are used to predict the expected crash rate and, consequently, expected crashes had the treatment not been implemented. This basic naïve 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 RTM bias.

#### 4.2. Before-after with empirical Bayes

The accurate estimation of the safety impacts of passing lanes on crashes might be challenging for various reasons; there are sundry safety-related factors such as changes in traffic volume, crash reporting threshold, and the probability of reporting that are not controllable during the B/A observational periods. Moreover, installing passing lanes is usually decided for operational and safety reasons,

**Table 4.** Societal crash cost estimate.

	Societal Crash Cost Estimate		
	Cost	Count	Cost
Fatal (K)	\$9,299,000.00	8	\$74,392,000.00
Disabling (A)	\$420,000.00	30	\$12,600,000.00
Evident (B)	\$127,000.00	50	\$6,350,000.00
Possible (C)	\$72,000.00	33	\$2,376,000.00
Total		121	\$95,718,000.00

therefore, it is necessary to account for the possible RTM bias in conducting safety analyses. In such circumstances, a methodology such as the commonly used and widely accepted EB method should be adopted (Persaud et al., 2013).

In the B/A with Empirical Bayes method, the expected crash frequencies at the treatment sites in the “after” period had the countermeasures not been implemented is estimated more precisely using data from the crash history of a treated site. Additionally, information about what is known about the safety of reference sites with similar yearly traffic trend, physical characteristics, and land use can be considered. In this study, Wyoming-specific SPFs were used to apply this known information.

The method is based on three fundamental assumptions (Hauer, 1997); (1) the number of crashes at any site follows a Poisson distribution, (2) the means for a population of systems can be approximated by a gamma distribution, (3) changes from year to year from sundry factors are similar for all reference sites.

One of the main advantages of the B/A 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 due to RTM bias. It is also a better approach than the simple naïve for accounting for influences of traffic volumes and time trends on safety. The estimate of the expected crashes at treatment sites is based on a weighted average of information from treatment and reference sites as given in (Hauer, 1997):

$$\hat{E}_i = (\gamma_i \times y_i \times n) + (1 - \gamma_i) \eta_i \tag{1}$$

Where,  $\gamma_i$  is a weight factor estimated from the overdispersion parameter of the negative binomial regression relationship and the expected “before” period crash frequency for the treatment site as shown in Equation 2:

$$\gamma_i = \frac{1}{1 + k \times y_i \times n} \tag{2}$$

Where,

$y_i$  = Number of the expected crashes of given type per year estimated from the SPF (represents the “evidence” from the reference sites)

$\eta_i$  = Observed number of crashes at the treatment site during the “before” period

$n$  = Number of years in the before period

$k$  = Overdispersion parameter.

The “evidence” from the reference sites is obtained as output from the SPF that is a regression model that provides an estimate of crash occurrences on a given roadway section. Crash frequency on a roadway section may be estimated using negative binomial regression models (7 and 12), and therefore the negative binomial form is used to fit the SPF using before period crash data of the reference sites with their

geometric and traffic parameters. A typical SPF will be of the following form:

$$y_i = e^{(\beta_0 + \beta_1 x_1 + \beta_2 x_2 + \dots + \beta_n x_n)} \quad (3)$$

Where,

$\beta_i$ 's = regression parameters

$x_1$  and  $x_2$  = logarithmic values of AADT and section length

$x_i$ 's ( $i > 2$ ) = other traffic and geometric parameters of interest.

Overdispersion parameter, denoted by  $k$ , is the parameter that determines how widely the crash frequencies are dispersed around the mean.

And the  $SD$  ( $\sigma_i$ ) for the estimate in Equation 1 is given by:

$$\hat{\sigma}_i = \sqrt{(1 - \gamma_i) \times \hat{E}_i} \quad (4)$$

It should be noted that the estimates obtained from Equation 1 are the estimates for number of crashes in the before period. Because it is required to get the estimated number of crashes at the treatment site in the after period, the estimates obtained from Equation 1 are to be adjusted for traffic volume changes and different before and after periods (11 and 13). The adjustment factors for which are given as follows:

Adjustment for AADT ( $\rho_{AADT}$ ):

$$\rho_{AADT} = \frac{AADT_{after}^{\beta_1}}{AADT_{before}^{\beta_1}} \quad (5)$$

Where,

$AADT_{after}$  = AADT in the after period at the treatment site

$AADT_{before}$  = AADT in the before period at the treatment site

$\beta_1$  = Regression coefficient of AADT from the SPF.

Adjustment for different B/A periods ( $\rho_{time}$ ):

$$\rho_{time} = \frac{m}{n} \quad (6)$$

Where,  $m$  = Number of years in the after period, and  $n$  = Number of years in the before period.

Final estimated number of crashes at the treatment location in the after period ( $\hat{\pi}_i$ ) after adjusting for traffic volume changes and different time periods is given by:

$$\hat{\pi}_i = \hat{E}_i \times \rho_{AADT} \times \rho_{time} \quad (7)$$

The index of effectiveness ( $\theta_i$ ) of the treatment is given by:

$$\hat{\theta}_i = \frac{\hat{\lambda}_i / \hat{\pi}_i}{1 + (\hat{\sigma}_i^2 / \hat{\pi}_i^2)} \tag{8}$$

Where,  $\hat{\lambda}_i$  = Observed number of crashes at the treatment site during the after period.

The percentage reduction ( $\tau_i$ ) in crashes of particular type at each site  $i$  is given by:

$$\hat{\tau}_i = (1 - \hat{\theta}_i) \times 100\% \tag{9}$$

The CMF ( $\hat{\theta}$ ) of the treatment averaged over all sites would be given by (14):

$$\hat{\theta} = \frac{\sum_{i=1}^m \hat{\lambda}_i / \sum_{i=1}^m \hat{\pi}_i}{1 + \left( \text{var} \left( \sum_{i=1}^m \hat{\pi}_i \right) / \left( \sum_{i=1}^m \hat{\pi}_i \right)^2 \right)} \tag{10}$$

Where,  $m$  = total number of treated sites, and based on Hauer (1997) (11):

$$\text{var} \left( \sum_{i=1}^k \hat{\pi}_i \right) = \sum_{i=1}^k \rho_{AADT}^2 \times \rho_{time}^2 \times \text{var}(\hat{E}_i) \tag{11}$$

The *SD* ( $\hat{\sigma}$ ) of the overall effectiveness can be estimated using information on the variance of the estimated and observed crashes, which is given by Equation 12.

$$\hat{\sigma} = \sqrt{\frac{\hat{\theta}^2 \left[ \left( \text{var} \left( \sum_{i=1}^k \hat{\pi}_i \right) / \left( \sum_{i=1}^k \hat{\pi}_i \right)^2 \right) + \left( \text{var} \left( \sum_{i=1}^k \hat{\lambda}_i \right) / \left( \sum_{i=1}^k \hat{\lambda}_i \right)^2 \right) \right]}{\left[ 1 + \left( \text{var} \left( \sum_{i=1}^k \hat{\pi}_i \right) / \left( \sum_{i=1}^k \hat{\pi}_i \right)^2 \right) \right]^2}} \quad (12)$$

$$\text{Where, } \text{var} \left( \sum_{i=1}^k \hat{\lambda}_i \right) = \sum_{i=1}^k \lambda_i \quad (13)$$

Equation 7 is used in the analysis to estimate the expected number of crashes in the after period at the treatment sites, and then the values are compared with the observed number of crashes at the treatment sites in the after period to get the percentage reduction in number of crashes resulting from the treatment.

### 4.3. Safety performance functions

*Level of service of safety* was defined by Kononov and Allery (2003) as how the roadway segment is performing in regard to its expected crash frequency and severity at a specific level of AADT. 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 roadways' improvements.

The EB method requires SPFs calibrated for similar reference sites (two-lane roadways in Wyoming). Wyoming-specific SPFs developed by WYDOT were used for total and F+I crashes, these SPFs were calibrated to match WYDOT-specific conditions using crash and traffic data from the whole state (WYDOT, 2014). Due to lack of SPFs for specific crash types for Wyoming conditions, crash proportions for target crashes were utilized in this study. It is worth mentioning that the AASHTO *Highway Safety Manual* (2010) also uses crash proportions to estimate specific crash types. The proportion of opposite direction sideswipe and head-on crashes, lane-departure crashes, and other types of crashes in interest were estimated from the *Wyoming Strategic Highway Safety Plan* (SHSP; WYDOT, 2012). The lane-departure crashes represent about 72% of total crashes. Among lane-departure crashes, opposite direction sideswipe and head-on crashes combined represent about 5.6% in the before period and 4.8% in the after period on undivided roadways in Wyoming.

#### 4.4. Overall cost comparison

When faced with a poorly performing section of two-lane highway transportation agencies have three basic options including do nothing, add passing lanes to target sections, or to upgrade to four lane (divided or undivided). The final option has the greatest benefits on safety because it prevents vehicles from having to travel in the opposing travel lane and limits merge and diverge maneuvers that occur at the end of passing lanes. The problem is that upgrading to four-lane either divided or undivided is very expensive compared to just constructing passing lanes in target areas. Now more than ever it is important to use highway funds wisely. The Congressional Budget Office is predicting a cash shortfall in the Highway Trust Fund that could mean a \$240 million cut in transportation funds for Wyoming (TripNet, 2014).

Using the Wyoming section of road as an example, it is easy to demonstrate that in addition to increased construction costs there are significant maintenance costs associated with the additional lanes especially when considering snow removal in the winter. The construction cost for the 10 miles of passing lanes in Wyoming was approximately \$5.85 million or \$585,000 per mile of passing lane. If this rate was used to calculate the cost to upgrade the entire 26-mile study section to four-lanes, the cost would be approximately \$15,220,400 for one direction or \$30,440,800 total for both directions. Alternatively, WYDOT's project development estimates the costs to approximately \$3.0 million per mile of four-lane highway which is even higher. Using this cost estimate it would cost over \$282 million to convert the whole 94-mile-long corridor to a four-lane divided highway but only \$14.5 million to add proposed passing lanes to the whole corridor (WYDOT Maintenance, 2014c).

Furthermore, the maintenance and snow removal costs per mile for passing lanes is only \$5,961, but if the road was upgraded to a four-lane highway the costs would rise to \$8,134 per mile (WYDOT Maintenance, 2014c). The increased construction costs for one four-lane section of road could be used to implement several passing lane projects throughout the state, where they are most needed. Moreover, the additional yearly maintenance and snow removal costs would take future resources from an even greater number of projects. Many agencies including WYDOT simply do not have the budget capable of providing this level of improvement without sacrificing potential benefits to the entire state's road system. Part of the reason that it is more cost effective to apply the limited resources that WYDOT does possess to construct passing lanes on target sections is that the relative safety benefit of passing lanes to four-lane highways varies compared to the cost differential (Wolldridge et al., 2001). Based on a review of the literature, it cannot be assumed that four-lane highways are safer than two-lane highways with passing lanes because increasing lanes can sometimes also increase the travel demand of the facility. Kononov and Allery (2003) identified a lack of understanding of the effect of number of lanes and traffic safety on freeways. They conducted a cross-

sectional study to compare slopes of SPFs of different numbers of lanes on freeways in different states. It was concluded that adding lanes on urban freeways initially resulted in safety improvement that 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 93% reduction in fatal crashes and a 71% drop in property damage only crashes (North Carolina Department of Transportation [NCDOT] Traffic Engineering and Safety, 2005–2007). In urban areas, results from previous studies indicated that raised median roadways are 25% to 30% safer than undivided roadways (Williams, Stover, Dixon, & Demosthenes, 2003).

Noland and Oh (2004) depicted conflicting findings that geometric improvements including roadway widening, adding lanes and reduction in curvature have no safety benefits. Abdel-Aty and Radwan (2000) found that the increase in number of lanes leads to crash rate increases on urban roadway sections.

Council and Stewart (2000) utilized cross-sectional analysis to evaluate the safety of converting two-lane roads to four-lane divided in four states: California, Michigan, North Carolina, and Washington. The results indicated a 40% to 60% reduction in total crashes. It is worth mentioning that their study found that the reduction in crashes appeared to decrease very slightly as AADT increased for California and North Carolina, whereas it increased with increases in AADT for Minnesota and Washington.

WYDOT (2014b) has recently updated the calculated societal crash cost estimates from the *HSM* KABCO scale to 2014 values. Fatal (K) crashes are \$9,299,000, disabling injury (A) \$420,000, evident injury (B) \$127,000, possible injury (C) \$72,000 and property damage only (O) \$32,000. Due to the relatively few amount of fatal crashes, the F+I crashes were combined for the safety effectiveness evaluation. The average of fatal, disabling, evident, and possible costs were approximately \$2,479,500. For the before and after study periods the 26 miles of road had approximately eight fatal, 30 incapacitating injuries, 50 nonincapacitating, and 33 possible injuries collisions. Using the societal costs provided by WYDOT (2014b) and averaging them this yields approximately \$95.5 million, as shown in Table 4.

## 5. Results and discussion

Often transportation agencies will conduct a simple observational B/A study to assess safety effectiveness. Although this approach is simple, a policy change should be made to highlight its poor reliability of results. To highlight this problem, this analysis approach was applied to the example road section in Wyoming. The observational B/A naïve method was applied on the nine passing lane segments and then also to the entire study area totaling 10.03 and 26.0 miles, respectively. This analysis was completed because it is most similar to the methods that

**Table 5.** Comparison of naïve and EB methods (safety effectiveness of whole corridor and sections with passing lanes).

Crash Type	Method			
	Naïve Before-After		EB Before-After	
	CMF (Safety Effectiveness)	S.E.	CMF (Safety Effectiveness)	S.E.
Whole corridor				
Total	0.79	0.03	0.68	0.08
F+I	-20.79%	-3.06%	-32.38%	-8.08%
Lane departure	1.23	0.01	0.80 <sup>a</sup>	0.14
	22.54%	-0.9%	-20.07%	-13.62%
Passing Lane segments	1.34	0.16	0.75	0.09
Total	34.04%	-16.20%	-24.93%	-9.25%
F+I	0.56	0.13	0.58	0.11
Lane departure	-44.16%	-13.45%	-41.60%	-10.63%
	0.73	0.03	0.67 <sup>a</sup>	0.18
Total	-26.91%	-2.82%	-33.50%	-18.29%
F+I	0.76	0.07	0.66	0.12
Lane departure	-24.44%	-6.86%	-34.25%	-12.26%

EB = Empirical Bayes, CMF = crash modification factor, F+I = Fatal+Injury  
<sup>a</sup> and <sup>b</sup> correspond with statistical significance levels at the 90%, and 80%, respectively.

transportation agencies employ due to their ease of use. The misleading results from this method can easily be seen when compared to results using the EB method in Table 5. Both methods were used to evaluate the safety effectiveness for the 26-mile passing lanes corridor and for only the nine passing lane sections within the entire corridor (passing lane sections constituted about 38% of the entire treated section). Crash rates were calculated using the mean AADT and length of segment for both section types. The CMFs were estimated based on crash rates for both individual passing lane locations and all locations combined and the Poisson test of significance was performed.

Overall, the total crash rate was reduced from 0.86 crashes per million vehicle miles (MVM) to 0.48 crashes per MVM for areas with passing lanes representing a 44% reduction in the total crash rate. Alternatively, the entire 26-mile study section total crash rate was reduced from 0.42 to 0.33 crashes per MVM that yields a 21% reduction in the total crash rate for the entire study section. The reduction of total crash rate was statistically significant.

The same approach was applied to F+I crashes only, the passing lane sections had reduced F+I crashes by 27%. Conversely, the entire study section had an increase of F+I crashes of 22.5% which may lead some transportation agencies to conclude that the countermeasure was not effective, but because this result was found using the naïve B/A method no conclusions should be made from it. When compared to the results of the EB method it shows that there was an increase in safety effectiveness. This example shows why it is so imperative that a policy change be made so that safety effectiveness is only concluded after sound statistical analysis like the EB method.

Using SAS 9.3, a procedure to apply the observational B/A was developed. The procedure was applied to the same sites mentioned in the previous section. The safety effectiveness of adding passing lanes was estimated using Wyoming-specific SPFs and observed crash history on the individual treatment sites and then the overall safety effectiveness was estimated using Equation 10. The EB method using Wyoming SPFs was applied to sections with passing lanes and the entire study corridor for total and F+I crashes. For example, the safety effectiveness of adding passing lanes across all locations was significantly improved by 41.60% and with standard error of 10.63% for F+I crashes. The statistical significance of the estimated safety effectiveness was calculated as:

$$\text{Abs}\left(\frac{\text{Safety Effectiveness}}{\text{SE}(\text{Safety Effectiveness})}\right) = \frac{41.60}{10.63} = 3.91 \quad (14)$$

Since  $\text{Abs}[\text{Safety Effectiveness}/\text{SE}(\text{Safety Effectiveness})]$  is  $\geq 1.96$ , it can be concluded that the treatment effect is significant at the 95% confidence level. The final results for passing lanes segments and the entire study section for total crashes and F+I crashes are presented and compared to other CMFs that were estimated using naïve B/A method in Table 5.

The results summarized in Table 5, indicate that the naïve and EB methods provided acceptable standard error especially considering the low traffic volumes. However, the results also show the importance of using a sound statistical approach like the EB method over the naïve method. The naïve B/A approach severely underestimated the treatment effects for F+I and lane-departure crashes on the whole corridor with CMFs equal to 1.23 and 1.34, respectively. When these CMFs are compared to the results obtained with EB analysis, the CMFs equal 0.80 and 0.75 at more than 80% confidence. Transportation agencies that rely on the policy of standard crash rate comparison and naïve B/A studies can easily end up with completely inaccurate conclusions about treatment affects. There are large differences between the naïve and EB results that highlight the necessity of changing the body of knowledge for accepted use of naïve studies.

## 6. Conclusions

When two-lane highways begin to underperform, passing lanes are often considered an appropriate countermeasure. Due to budgetary constraints and relative safety benefit (Potts & Harwood, 2004), WYDOT decided to construct nine passing lanes on a 26-mile stretch of rural two-lane highway. After collecting crash data for 7 years, it appeared that the safety benefit was negligible at best, and that F+I crashes had a slight increase based on basic B/A analysis using number of crashes and traffic volumes. However, once the EB and Wyoming-specific SPFs (Kononov & Allery, 2010) were applied, it was shown that the basic approach used

by WYDOT underestimated the benefit to F+I and lane-departure crashes and that the passing lanes had significant safety improvements.

The results from this article indicate that adding passing lanes to WY59 resulted in a crash reduction of 27% for F+I crashes and 44% for total crashes in areas with passing lanes. By using an example from Wyoming, it can be concluded that transportation agencies should consider implementing passing lanes instead of four-lane highways on poor performing two-lane highways and that the safety effectiveness should always be evaluated by performing a reliable statistical analysis such as EB instead of simple B/A comparisons.

As discussed previously, the construction cost for 10 miles of passing lanes was approximately \$5.8 million compared to an estimated cost of more than \$30 million for four-lane construction. In addition to enormous discrepancies between construction costs, passing lanes also were found to have significantly lower maintenance and snow removal expenses. The hefty four-lane project expenditures should instead be weighed against the opportunity to use those funds to construct several target passing-lane projects throughout a state's roadway network. This is especially true considering the relative safety benefits of passing lanes outlined in this article and the regularity of constrained transportation budgets.

Moreover, the analysis in this study should be applied to other Wyoming two-lane highways with passing lanes to confirm findings and to aid future transportation decisions statewide. The findings from this analysis of policy options can be used by transportation agencies across the country in justification and evaluation of two-lane highway improvements.

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