Safety Evaluation of Offset Improvements for Left-Turn Lanes

Bhagwant Persaud[1]
Department of Civil Engineering, Ryerson University
350 Victoria Street, Toronto, Ontario M5B 2K3, Canada
Phone: (416) 979-5000, Ext. 6464
e-mail: bpersaud@ryerson.ca

Craig Lyon
Persaud & Lyon, Inc.
663 Gainsborough Avenue
Ottawa, Ontario, Canada K2A 2Y9
Phone: (613) 422-2542
e-mail: craig.lyon@rogers.com

Frank Gross
Vanasse Hangen Brustlin, Inc
333 Fayetteville St Suite 1450
Raleigh, NC 27601
Phone: (919) 834-3972
e-mail: FGross@vhb.com

Kimberly Eccles
Vanasse Hangen Brustlin, Inc
333 Fayetteville St Suite 1450
Raleigh, NC 27601
Phone: (919) 834-3972
e-mail: KEccles@vhb.com

Key Words: Offset left-turn lanes; safety evaluation; empirical Bayes; intersection safety

Word Count: 5384 text words + 2 Figures + 6 Tables = 7384 words

[1] Corresponding author

ABSTRACT

This study provides a safety evaluation of offset improvements for left-turn lanes, a treatment intended to reduce the frequency of crashes by providing better visibility for drivers who are turning left. Geometric, traffic, and crash data were obtained for installations in Nebraska, Florida and Wisconsin, and for a number of untreated reference sites in each State. To account for potential selection bias and regression-to-the-mean, an empirical Bayes before-after analysis was conducted. There was a large difference in observed effects among the three States, which may be explained, in part, by the variety of offset improvements applied. Florida and Nebraska employed pavement marking adjustments or minor construction to improve the offset, but most improvements did not result in a positive offset. Wisconsin, on the other hand, reconfigured left-turn lanes through major construction projects, resulting in significant positive offsets. Not surprisingly, therefore, Wisconsin showed significant reductions in all crash types investigated – total (34 percent), injury (36 percent), left-turn (38 percent), and rear-end (32 percent), while results in Florida and Nebraska showed little or no effect on total crashes. For Nebraska, a disaggregate analysis did reveal, however, that the percent reduction in crashes increases as the expected number of crashes increases. An economic analysis indicated that offset improvement through reconstruction is cost-effective at intersections with at least nine expected crashes per year and where left-turn lanes are justified by traffic volume warrants.

INTRODUCTION

The FHWA has organized a Pooled Fund Study, involving 26 States, to evaluate low-cost safety strategies as part of the Strategic Highway Safety Plan developed by the American Association of State Highway and Transportation Officials (AASHTO) Standing Committee on Highway Traffic Safety. The purpose of the Pooled Fund Study is to evaluate the safety effectiveness of several tried and experimental low-cost safety strategies through scientifically rigorous crash-based or simulation-based studies. Based on inputs from the Pooled Fund Study Technical Advisory Committee and the availability of data, installing offset left-turn lanes at signalized intersections was selected as a strategy that should be evaluated as part of this effort. This strategy may be particularly helpful for older drivers *(1).*

The motivation for the selected strategy is that the typical geometry of signalized intersections can present several challenges. Visibility of oncoming vehicles is important for drivers to identify acceptable gaps. Typical intersection alignments have opposing left-turn lanes directly across from one another and immediately adjacent to the through lanes as shown in Figure 1(b). Thus, a left-turning vehicle in the opposite left-turn lane can obstruct the view of oncoming vehicles. The geometry at some intersections actually creates a negative offset as shown in Figure 1(a), which further reduces sight distance for left-turning vehicles. Sight distance for left-turning vehicles can be improved, as shown in Figure 1(c) by shifting the left-turn lanes to the left to create a positive offset *(1).* When initial offsets are negative, a variation of the offset improvement strategy can be applied by increasing the lateral separation between the left-turn and adjacent through lane (i.e., modifying the left-turn lane from a negative to less negative offset). Hence, the offset is still negative, but sight distance to oncoming vehicles is slightly improved.

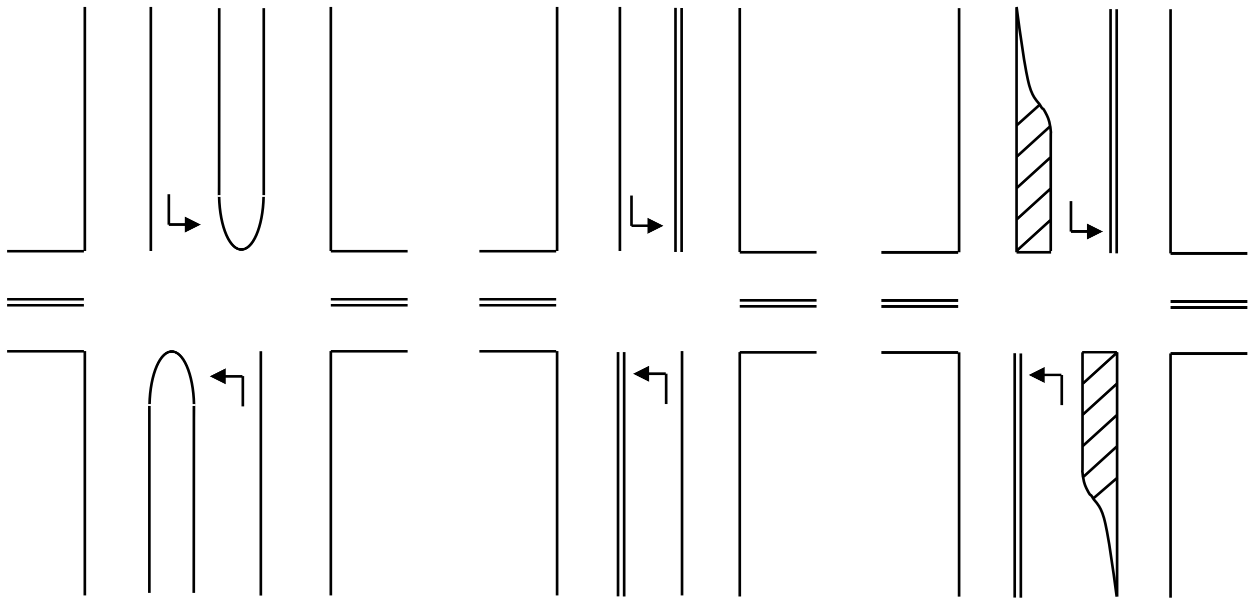

FIGURE 1 Illustration of Negative, No, and Positive Offset Left-turn Lanes.

The literature on the safety effects of offset improvements for left-turn lanes is not definitive. Khattak et al. *(2)* evaluated the installation of offset left-turn lanes at urban signalized intersections in Nebraska. These offsets were created by increasing the lateral separation between the left-turn lanes and the adjacent through lanes, thereby improving the sight distance for left-turning vehicles. Six intersections were treated and two intersections without offset left-turn lanes were selected as a comparison group. The results indicated reductions of 27 percent and 40 percent for total and property damage only (PDO) accidents, respectively.

Staplin et al. *(3)* studied the effects of offset distance, both positive and negative, between opposing left-turn lanes on the turning performance of drivers with respect to driver age and gender. Left-turn performance of 100 subjects was evaluated under normal driving conditions at four intersections with different left-turn offset configurations. The results indicated that driver performance can be adversely affected by offsets that are more than 0.9-m (2.95-ft.) negative offset. Such large negative offsets significantly increase the size of the critical gaps of drivers turning left and also seem to increase the likelihood of conflicts between left-turns and opposing through traffic. Surprisingly, driver perceptions of the level of comfort and degree of difficulty were not found to improve with the increased sight distance provided by larger (i.e., more positive) offsets. The 1.8-m positive offset was associated with a lower level of comfort and a higher degree of difficulty perceived by drivers making left-turns than the 0.9-m (2.95-ft.) negative offset, which provided less sight distance. This may have been because the 0.9-m (2.95-ft.) negative offset is much more common than the 1.8-m (5.9-ft.) positive offset.

This strategy may be particularly well suited for older drivers. Several studies have found that older drivers have more left-turn accidents at signalized intersections than younger drivers do *(4)*. Common older driver errors include misjudging the oncoming vehicle speed, misjudging the available gap, assuming that the oncoming vehicle was going to stop or turn, and simply not seeing the other vehicle. Further, older drivers may experience greater difficulties at intersections as a result of diminished visual capabilities, such as depth and motion perception. These traits associated with older drivers can lead to collisions between vehicles turning left from the major road and through vehicles on the opposing major-road approach *(4)*.

Given the paucity of literature on the subject, the basic objective of the study (*5*) on which this paper is based was to estimate the change in target crashes following the installation of offset improvements for left-turn lanes at signalized intersections. Target crashes include total crashes, injury crashes, left-turn opposing crashes, and rear-end crashes.

A further objective was to conduct a disaggregate analysis to investigate whether there are special circumstances that are particularly favourable for the installation of offset improvements for left-turn lanes. This required an examination of the impact of factors such as traffic volumes and the level of crashes before treatment, and an economic analysis to assess the circumstances under which the treatment would be cost-effective.

METHODOLOGY

The empirical Bayes (EB) methodology for observational before-after studies *(6)* was used for the evaluation. In this approach, the change in safety for a given crash type at a site is given by:

$$\Delta\ Safety = \lambda - \pi \qquad (1)$$

where:

λ is the expected number of crashes that would have occurred in the after period without the strategy.

π is the number of reported crashes in the after period.

In estimating λ, the effects of regression-to-the-mean and changes in traffic volume were explicitly accounted for using safety performance functions (SPFs) relating crashes of different types to traffic flow and other relevant factors for each jurisdiction *based on untreated sites*. Annual SPF multipliers were calibrated to account for the temporal effects (e.g., variation in weather, demography, and crash reporting) on safety.

In the EB procedure, the SPF is used to first estimate the number of crashes that would be expected in each year of the before period at locations with traffic volumes and other characteristics similar to the one being analyzed. The sum of these annual SPF estimates (*P*) is then combined with the count of crashes (*x*) in the before period at a strategy site to obtain an estimate of the expected number of crashes (*m*) before strategy. This estimate of *m* is:

$$m = w_1(x) + w_2 P \qquad (2)$$

where:

w_1 and w_2 are estimated from the mean and variance of the SPF estimate as:

$$w_1 = \frac{P}{P + 1/k} \qquad (3)$$

$$w_2 = \frac{1}{k(P + 1/k)} \quad (4)$$

where:

k is a constant for a given model and is estimated from the SPF calibration process with the use of a maximum likelihood procedure. (In that process, a negative binomial error structure is assumed with k being the dispersion parameter of this distribution.)

A factor is then applied to m to account for the length of the after period and differences in traffic volumes between the before and after periods. This factor is the sum of the annual SPF predictions for the after period divided by P, the sum of these predictions for the before period. The result, after applying this factor, is an estimate of λ. The procedure also produces an estimate of the variance of λ.

The estimate of λ is then summed over all sites in a strategy group of interest (to obtain λ_{sum}) and compared with the count of crashes during the after period in that group (π_{sum}). The variance of λ is also summed over all sites in the strategy group.

The Index of Effectiveness (θ) is estimated as:

$$\theta = \frac{\pi_{sum}/\lambda_{sum}}{1 + \left(Var(\lambda_{sum}) / \lambda_{sum}^2 \right)} \quad (5)$$

The standard deviation of θ is given by:

$$StDev(\theta) = \sqrt{\frac{\theta^2 \left(\frac{Var(\pi_{sum})}{\pi_{sum}^2} + \frac{Var(\lambda_{sum})}{\lambda_{sum}^2} \right)}{\left(1 + \frac{Var(\lambda_{sum})}{\lambda_{sum}^2} \right)^2}} \quad (6)$$

The percent change in crashes is calculated as $100(1-\theta)$; thus a value of $\theta = 0.7$ with a standard deviation of 0.12 indicates a 30 percent reduction in crashes with a standard deviation of 12 percent.

DATA COLLECTION

Data were collected for a total of 105 installations at signalized intersections in three States: Wisconsin, Florida and Nebraska. To the best of the research team's knowledge, the offset-left improvements were the only significant changes implemented at these intersections during the analysis period. During the data collection process, the project team identified variations in the design of offset left-turn lanes in the three States. For example, nearly all installations in Wisconsin were similar to the positive offset left-turn lane concept identified in the *NCHRP Report 500 Series Volume 12* (*1*) and shown previously in Figure 1(c). However, many of the installations in Florida and Nebraska did not result in a positive offset. Instead, the offset was improved by shifting the left-turn lane further away from the adjacent through lane, but the end result was a less negative offset or no offset (refer to Figure 1 for definitions). Due to the variation in offset designs among the States, the project team adopted a classification scheme to define the installations as one of three types of offset improvements. The adopted classification scheme is presented below and examples of the three types of offset improvements are provided in Figure 2.

- Type 1 – Positive Offset: The left-turn lanes are shifted to the left to enhance sight distance for opposing left-turn drivers (Figure 2, left).
- Type 2 – Lateral Separation with No Offset: The left-turn lanes are separated from the adjacent through lanes, but opposing left-turn lanes are directly aligned with no offset or a very slight positive offset (Figure 2, center).
- Type 3: Lateral Separation with Negative Offset: The left-turn lanes are separated from the adjacent through lanes, but opposing left-turn lanes are still negatively offset (Figure 2, right), although less negatively offset than in the before period.

FIGURE 2 Example of Nebraska Type 1 (left), Type 2 (center), and Type 3 (right) treatments.

Florida

In total, 13 locations were identified in three districts. Of these, 8 installations were defined as Type 3 according to the classification scheme. District engineers also provided a list of 39 signalized intersections with conventional left-turn lanes (no offset) to be used as reference sites in the EB analysis.

The Florida Department of Transportation (DOT) provided a crash database containing all crashes on state-maintained roads from 1983 to 2005, inclusive. The database also contained information for several other variables including average daily traffic, number of lanes, area type, roadway type, and speed limit. The crash data were matched to the strategy and reference sites using the section number and intersection milepost. A radius of 250 ft was used to identify crashes at the intersections.

Some roadway data elements were available in the crash database provided by the Florida DOT, including number of lanes, area type, roadway type, and speed limit. The presence and type of median as well as the number of left-turn, through, and right-turn lanes were identified using aerial images. For locations where the images were not clear, field visits were conducted to obtain the data.

Traffic volumes on the major road were available through the crash database provided by the Florida DOT because all major approaches were state-maintained roads. Minor road data were not available through the crash database unless the minor road was also a state-maintained route. In most cases, the minor road traffic volume had to be obtained from the county where the site was located. When available, county websites were used to obtain the necessary traffic volume data. In other cases, the county engineers were asked to provide estimates of the minor road traffic volume.

Nebraska (City of Lincoln)

The City of Lincoln Department of Public Works provided a list of signalized intersections where offset left-turn lane improvements had been implemented. The list indicated the type of median and type of left-turn signal phasing (i.e., permissive, protected-permissive, permissive-protected, or fully-protected), but did not indicate the type of offset improvement. Those sites with fully-protected left-turn signal phasing were excluded from the analysis, as were sites with inadequate traffic volume data, leaving a total of 92 intersections to be included in the analysis. The majority of offset improvements (44) included the reconfiguration of existing left-turn lanes to Type 2 offsets. There were 9 intersections with Type 1 offset left-turn lanes included in the study and 39 intersections with Type 3 improvements.

The City of Lincoln provided a list of potential reference locations, which were signalized but untreated (i.e., no offset treatment). The final list of reference sites was selected based on data availability, resulting in a total of 64 reference sites.

The numbers of left-turn, through, and right-turn lanes were identified using electronic intersection design files from the city or aerial images. For locations where the images were not clear, field visits were conducted to obtain the necessary data.

Traffic volume data were obtained directly from the City of Lincoln which maintains traffic counts on their website. Traffic volumes were available for 1998, 1999, 2000, 2002, and 2006. When the subject intersection was located between two count locations, an average of the two closest counts was computed. Growth factors were then computed and applied to the traffic volumes to fill-in the data for years that were not available.

The Nebraska Department of Roads (NDOR) helped to provide crash data for each of the strategy and reference sites from 1994 to 2006. NDOR does not use a specific distance to determine whether a crash is "intersection-related". Rather, intersection-related crashes are identified by an analyst after careful review of each case. Specifically, crashes were included in this group if any of the vehicles involved was in the process of stopping, turning, slowing down, or making any other type of maneuver that was a result of the presence of an intersection.

Wisconsin

The University of Wisconsin provided a list of potential installation locations including the region, project number, and intersection name. In total, 12 locations were identified in two regions. Of these, 10 were Type 1 and only 2 were Type 2. One region provided detailed cost information for each project.

Wisconsin Department of Transportation (WisDOT) provided a database of all state-maintained signalized intersections. This database was used to identify possible reference sites that were similar to the intersections included in the treatment group, but did not have offset improvements. The final reference group was selected based on the availability of traffic volume and intersection data.

WisDOT provided an electronic roadway inventory that included information on designation as urban or rural, whether the roadway was divided or undivided, and the presence of a shoulder. Specific intersection geometry items such as lane designations were obtained from aerial photography.

Traffic volumes were obtained from county AADT maps. Traffic volumes were not available for every year during the study period and the years of available traffic counts varied by site. Linear interpolation was used to fill-in years where counts were not available.

WisDOT provided electronic crash data from 1994 to 2006. The crash data were matched to the strategy and reference sites using the major and minor road names. A radius of 250 ft (76.2 m) was used to identify crashes at both the strategy and reference intersections.

Data Summary

Table 1 provides the definitions of crash types used while Table 2 provides summary information for the data collected. For the Florida data, the vehicle direction and movement were used to identify specific target crashes occurring on the treated roadway. The crash data from Nebraska did not include information on each vehicle involved prior to 2002. Thus, the left-turn and rear-end crashes could not be restricted to only those occurring on the treated roadways and all crashes identified as rear-end and left-turn were included. The Wisconsin crash data only included crashes coded to the mainline (treated approaches) and did not include the initial vehicle direction. As such, crash data in Wisconsin were coded as left-turn-related if a vehicle was turning left and the crash was not coded as rear-end.

TABLE 1 Definitions of Crash Types.

State	Total	Injury	Left-Turn Opposing	Rear-End
Florida	All within 250 ft (76.2 m) of intersection and identified as at-intersection or intersection-related	K,A,B,C on KABCO scale	Vehicles approaching from opposite directions on treated roadway; one turning left; the other going straight	Both vehicles approaching from same direction on treated roadway; both going straight; or one proceeding straight and one turning left
Nebraska	All crashes identified as intersection-related	K,A,B,C on KABCO scale	Defined as left-turn opposing	Defined as rear-end
Wisconsin	Only includes crashes on the mainline within 250 ft (76.2 m) of the intersection	K,A,B,C on KABCO scale	Includes any mainline crash with a left-turning vehicle and not coded as rear-end; includes crashes where one is proceeding straight and one is turning left	On the main-line and defined as rear-end

TABLE 2 Data Summary for Treatment and Reference Sites.
(before and after period data shown separately for the treatment sites)

Variable	Florida		Nebraska		Wisconsin	
	Treatment	Reference	Treatment	Reference	Treatment	Reference
Number of sites	13	36	92	64	12	63
Site-years before Site-years after	120.6 72.8	576	644.0 368.0	704	87.0 33.0	693
Crashes/site/year before Crashes/site/year after	11.1 12.9	6.59	7.1 7.6	5.68	7.7 4.7	7.1
Injury crashes/site/year before Injury crashes/site/year after	6.5 6.5	3.87	3.9 3.9	3.10	3.5 1.9	2.9
Left-turn opposing crashes/site/year before Left-turn opposing crashes/site/year after	1.8 1.5	0.75	1.2 1.9	0.82	3.3 (left turn) 1.8 (left turn)	2.2 (left turn)
Rear-end crashes/site/year before Rear-end crashes/site/year after	2.3 3.7	1.83	3.1 3.6	2.66	2.2 1.5	2.8
Major Road AADT before (Average, Minimum, Maximum) Major Road AADT after (Average, Minimum, Maximum)	43,237 28,587 58,051 45,960 35,514 56,509	40,837 18,812 68,115	20,454 3,067 38,300 22,878 5,800 37,300	16,400 4,500 36,800	19,548 8,175 33,050 18,892 7,150 29,200	20,966 5,750 51,000
Minor Road AADT before (Average, Minimum, Maximum) Minor Road AADT after (Average, Minimum, Maximum)	10,506 1,582 36,731 11,145 1,810 34,999	5,366 2,129 12,609	10,605 1,500 20,267 11,836 3,100 24,800	8,282 1,600 16,800	7,028 2,300 12,575 6,668 2,200 13,350	Not available

Note: 37 treatment intersections in Nebraska, 1 in Florida, and 2 in Wisconsin did not have minor road volumes.

It is evident from Table 2 that the crash frequencies and major road volumes for the Nebraska and Wisconsin treatment sites are reasonably similar and substantially lower than the values for Florida. Needless to say, the information in Table 2 should not be used to make simple before-after comparisons of crashes per-site year since such an analysis would not account for factors other than the strategy that may cause safety to change between the two periods. Such comparisons are properly done with the empirical Bayes analysis.

DEVELOPMENT OF SAFETY PERFORMANCE FUNCTIONS

This section presents the safety performance functions (SPFs) developed for use in the empirical Bayes methodology *(6)*. Generalized linear modeling was used to estimate model coefficients assuming a negative binomial error distribution, which is consistent with the state of research.

SPFs were calibrated separately for each of the three jurisdictions. The primary form of the SPFs is:

$$\text{Crashes/year} = \alpha(\text{MajAADT})^{\beta 1}(\text{MinAADT})^{\beta 2} \quad (7)$$

or, where minor road AADT are unavailable,

$$\text{Crashes/year} = \alpha(\text{MajAADT})^{\beta 1} \quad (8)$$

where

MajAADT is the average daily traffic on the major roadway.

MinAADT is the average daily traffic on the minor roadway.

α, β_1, β_2 are parameters estimated in the SPF calibration process.

The SPFs without minor road AADT were calibrated for applying only to those sites without this information. In specifying a negative binomial error structure, the dispersion parameter, *k*, relates the mean and variance of the SPF estimate. This parameter is used in Equations 3 and 4 of the EB procedure and is estimated iteratively from the generalized linear model.

The safety performance functions developed are presented in Tables 3, 4, and 5. For some crash types in Florida and Nebraska, there were insufficient data to directly estimate SPFs. For these it was necessary to apply a multiplier to the total crash model, estimated as the ratio of the number of crashes of that type to total number of crashes.

TABLE 3 Safety Performance Functions for Florida*

Parameter	Crash Type	Crashes/year = $\alpha(\text{MajAADT})^{\beta 1}(\text{MinAADT})^{\beta 2}$			Crashes/year = $\alpha(\text{MajAADT})^{\beta 1}$		
		Estimate	Standard Error	Pr > Chisq	Estimate	Standard Error	Pr > Chisq
ln(α)	Total	-12.7694	3.5721	0.0004	-9.9989	3.1435	0.0015
	Injury	-10.8768	3.5227	0.0020	-7.9837	3.0636	0.0092
	Rear-end	-12.9905	5.0389	0.0099	-11.5082	3.8283	0.0026
β1	Total	0.8275	0.3220	0.0102	1.1192	0.2973	0.0002
	Injury	0.6296	0.3126	0.0440	0.8800	0.2897	0.0024
	Rear-end	0.8555	0.4567	0.0611	1.1438	0.3619	0.0016
β2	Total	0.6865	0.2270	0.0025			
	Injury	0.6499	0.2205	0.0032			
	Rear-end	0.5259	0.3098	0.0896			
k	Total	0.2596			0.3087		
	Injury	0.2504			0.2970		
	Rear-end	0.5175			0.4460		

* For Left-Turn Opposing: Apply model for total crashes with a multiplier of 0.11.

TABLE 4 Safety Performance Functions for Total Crashes in Nebraska*

Parameter	Crashes/year = $\alpha(MajAADT)^{\beta 1}(MinAADT)^{\beta 2}$			Crashes/year = $\alpha(MajAADT)^{\beta 1}$		
	Estimate	Standard Error	Pr > Chisq	Estimate	Standard Error	Pr > Chisq
ln(α)	-8.9123	2.0587	<0.0001	-8.8157	2.0929	<0.0001
β1	0.8317	0.2498	0.0009	1.0868	0.2170	<0.0001
β2	0.2783	0.1454	0.0550			
k	0.2815			0.2979		

* For Left-Turn Opposing: Apply model for total crashes with a multiplier of 0.15; For Injury: Apply model for total crashes with a multiplier of 0.54; For Rear-end: Apply model for total crashes with a multiplier of 0.47.

TABLE 5 Safety Performance Functions for Wisconsin

Parameter	Crash Type	Crashes/year = $\alpha(MajAADT)^{\beta 1}(exp^{\beta 2(totalthrumaj)})$		
		Estimate	Standard Error	Pr > Chisq
ln(α)	Total	-5.8564	1.5239	0.0001
	Injury	-5.516	1.6023	0.0006
	Left-turn	-4.7532	2.1052	0.024
	Rear-end	-11.111	1.8213	<.0001
β1	Total	0.7208	0.1678	<.0001
	Injury	0.5711	0.1754	0.0011
	Left-turn	0.4406	0.2309	0.0563
	Rear-end	1.217	0.1841	<.0001
β2	Total	0.1421	0.0748	0.0575
	Injury	0.2016	0.0757	0.0077
	Left-turn	0.2538	0.1034	0.0141
	Rear-end	0		
k	Total	0.2446		
	Injury	0.2455		
	Left-turn	0.4250		
	Rear-end	0.3931		

Note: Totalthrumaj = total thru' lanes on the major road

RESULTS

Each jurisdiction's data were analyzed separately and a composite effect was obtained for all sites in each State. A disaggregate analysis was conducted for the Nebraska sites by grouping sites by various characteristics. A disaggregate analysis was not conducted for Florida or Wisconsin because of the small sample sizes. Florida and Wisconsin sites could not be combined with Nebraska for the disaggregate analysis because of the substantially higher AADTs and crash frequencies in Florida and the predominance of Type 1 installations in Wisconsin compared to the other two States.

Aggregate Analysis

Table 6 presents the results of the aggregate analysis. Combined effects for the three analyses are not estimated because the treatments and their effects vary significantly among the jurisdictions. The following points summarize the results for the individual State analyses:

- In Wisconsin, where the analysis focused on crashes involving mainline vehicles only, and where the installations were predominantly Type 1 (positive offset) the results indicate substantial and highly significant crash reductions in all categories – total, injury, left-turn, and rear-end.
- The Nebraska and Florida results show little or no evidence that this strategy is effective overall (i.e., for total crashes) in these jurisdictions. Installations in these States were mostly Type 2 or 3 (no offset or negative offset).
- For left-turn opposing crashes, a reduction in crashes was found in Florida, although not significant. By contrast, a highly significant increase in left-turn opposing crashes was found in Nebraska. This is likely because the positive effects for sites where the strategy might be worthwhile and warranted are diluted by effects at those where the strategy may not be justified by a specific safety concern. In particular, a majority of all signalized intersections in the Nebraska study area were treated, raising the possibility that, at some intersections, this strategy may not have been justified. In addition, the surprisingly negative effects for left-turn opposing crashes may be due to the inability to control for possible increases in left-turn traffic because turning movement counts were unavailable.
- For rear-end crashes, there was a small and insignificant increase in Florida. In Nebraska, rear-end crashes also increased slightly and this increase was statistically significant.

TABLE 6 Aggregate Results*

(Negative sign indicates an increase in crashes. Bold denotes effects that are significant at the 95% confidence level)

	State	**Total**	**Injury**	**Left Turn (All or opposing)***	**Rear-End**
EB estimate of crashes expected in the after period without strategy	Florida	969.9	471.7	118.8	257.9
	Nebraska	2795.81	1536.12	478.96	1248.64
	Wisconsin	233.77	95.88	94.85	72.76
Count of crashes observed in the after period	Florida	938	472	106	273
	Nebraska	2811	1441	695	1335
	Wisconsin	155	62.0	59	50
Estimate of percent reduction (and standard error)	Florida	3.4 (4.7)	0.2 (6.6)	11.4 (11.2)	-5.3 (9.9)
	Nebraska	-0.5 (2.4)	**6.2 (3.0)**	**-45.0 (6.7)**	**-6.9 (3.6)**
	Wisconsin	**33.8 (6.0)**	**35.6 (9.0)**	**38.0 (8.9)**	**31.7 (20.9)**

* Nebraska and Florida analyses were based on left-turn opposing crashes; For Wisconsin these could not be precisely identified; thus the analysis included all non-rear-end crashes involving a left-turning vehicle.

Disaggregate Analysis

A disaggregate analysis was completed for Nebraska, the only State with a sufficient sample size to facilitate this analysis. The objective was to determine if safety effects are more or less pronounced for specific conditions. For this analysis, crash effects were estimated for groups of sites categorized by a number of variables, including type of offset, median type, number of lanes, crash frequency and traffic volume. Other variables that may have been of interest were not available in the database. Total crashes were the only crash type included in the disaggregate analysis because of the counterintuitive results for left-turn opposing crashes. Also, there are fewer target crashes than total crashes, which reduces the certainty of a disaggregate analysis. While the disaggregate analyses indicate significant crash reductions for specific circumstances, these estimates are based on limited sample sizes and are not intended to be used as individual crash reduction factors.

The variable found to be most related to the safety effectiveness was the expected number of crashes in the before period. Analysis revealed that the percent reduction in crashes increases as the expected number of crashes (before treatment) increases. For example, the 30 sites in Nebraska with 9 or more expected crashes per year in the before period had an 8 percent reduction in crashes, compared to an insignificant 0.5 percent increase in crashes for all 92 Nebraska locations. This finding seems logical in that safety treatments are generally expected to be most effective where a safety problem is manifested in a high frequency of crashes.

ECONOMIC ANALYSIS

The economic analysis was conducted from two perspectives. First, a benefit-cost ratio was estimated for Wisconsin, the only State for which an overall safety benefit was detected. Second, the disaggregate analysis for Nebraska was used to identify the level of expected number of crashes that would yield a crash reduction to justify the construction costs.

Wisconsin installations were almost all of the Type 1 variety, involving major reconstruction with capital costs that averaged $315,873 and an estimated service life of 20 years. Assuming a discount rate of 2.8 percent for a 20-year service life, as suggested by the Office of Management and Budget *(7)*, this translates into an annualized cost of $20,840. Wisconsin was the only State for which a safety benefit was detected overall and for which a benefit-cost ratio could be estimated. Using recent FHWA comprehensive crash cost estimates *(8)* for signalized intersections with approach speeds less than 45 mph (72.4 km/h), the unit crash costs were identified as $15,788 for head-on crashes and $23,872 for rear-end crashes. These estimated costs include all severities combined.

The results in Table 6 suggest a reduction of 2.39 total crashes per site-year (subtracting the observed crashes in the after period from the expected crashes and dividing by the total site-years from Table 2). Using the lower comprehensive crash cost ($15,788) as a conservative estimate of the benefit, the savings due to the reduced crashes is $37,733. This value compares favorably to the annualized installation cost of $20,840 giving (conservatively) a benefit-cost ratio of 1.8.

Nebraska installations were mostly of the Type 2 and 3 variety, typically involving a simple modification of an existing left-turn bay (typically 150 ft (45.7 m) long) for which the striping was reconfigured with thermoplastic to improve the offset. The estimated cost was $200 per approach with an 8 to 10 year service life, depending on traffic volumes. Florida installations were more elaborate versions of the Type 2 and 3 installations, involving the shifting of the left-turn lanes further into the median (on divided highways). The estimated cost is $15,000 per approach assuming a left-turn bay length of 150 ft (45.7 m) and a lane width of 12 ft (3.66 m). The service life is estimated to be 14 years.

The disaggregate analysis for Nebraska showed that the strategy may be effective if implemented at sites with high crash frequencies. Based on the disaggregate results, it was possible to estimate crash frequency levels for which implementation of the strategy would be economically justified. Restriping costs, similar to those in Nebraska, are so minimal that it can be assumed that this measure can be implemented at any signalized intersection with sufficient left-turn traffic to justify a left-turn lane and permissive or protected-permissive phasing. Therefore, the focus of the economic analysis was to determine the crash reduction factor and crash frequency levels that would justify the more expensive Type 2 and 3 treatments, similar to the Florida installations, and which would involve minor construction. Based on a discount rate of 2.7 percent, as suggested by the Office of Management and Budget *(7)* for a 10 to 15 year service life, and assuming that four approaches are reconstructed, the annualized cost is $5,067. The cost requires an annual crash savings of $10,134 to justify an installation based on a 2:1 benefit cost ratio.

The required crash savings, as a dollar value, can be converted into crash frequency using the recent FHWA comprehensive crash cost estimates *(8)*. As before, for signalized intersections with approach speeds less than 45 mph (72.4 km/h), the unit costs for crashes of all severities combined range from $15,788 for head-on crashes to $23,872 for rear-end crashes. Again, using the lower crash cost as a conservative estimate, the annual crash reduction needed to justify the installation cost is 0.64 crashes per year (i.e., a 2:1 benefit-cost ratio is calculated as $10,134/$15,788 = 0.64 crashes/year). The disaggregate analysis indicates that the crash benefits increase as the expected number of crashes increase. The required crash benefit of 0.64 crashes per year could be achieved at intersections with 9 or more expected crashes per year, for which the crash reduction factor is at least 8 percent. Thus, the installation of the Type 2 and 3 varieties of this strategy through reconstruction similar to the Florida installations appears to be cost-effective at intersections with at least 9 expected crashes per year and where left-turn lanes are justified by traffic volume warrants.

SUMMARY AND CONCLUSIONS

The empirical Bayes evaluation of the safety effectiveness of implementing offset improvements for left-turn lanes at signalized intersections was based on 92 installations in Nebraska, 13 in Florida, and 12 in Wisconsin. The offset improvements varied greatly in the three States. Many of the installations in Florida and Nebraska resulted in a less negative offset or no offset, rather than a positive offset. The results for these two States show little or no evidence that would suggest that this strategy is effective for reducing total crashes. Wisconsin installations, on the other hand, involved major reconstruction to improve the offset and all but two were conversions from negative or no offset to a positive offset. Not surprisingly the Wisconsin results indicate substantial and highly significant crash reductions in total, injury, left-turn, and rear-end crashes.

The disaggregate analysis, based on the Nebraska data, revealed that the percentage reduction in crashes increases as the expected number of crashes increases. For example, the 30 sites with an expected frequency of nine or more crashes per year in the before period had an 8.0 percent reduction in crashes (significant at the 5 percent level), compared to an insignificant 0.5 percent increase in total crashes for all 92 Nebraska locations. This finding seems logical in that safety treatments are generally expected to be most effective where a safety problem is manifested in a high frequency of crashes.

On the basis of this disaggregate analysis, the economic analysis sought to identify the level of expected number of crashes that would yield a crash benefit that would justify the construction cost. Based on this analysis, Type 2 or Type 3 installations through reconstruction, as was undertaken in Florida, are cost-effective at intersections with at least nine expected crashes per year, for which the expected reduction in crashes is at least 8 percent. This information could be used by engineers in selecting and prioritizing locations for this treatment. Needless to say, the left turn lanes should, in the first place, be justified by traffic volume warrants.

The results do support the continuing use of this treatment, particularly for the circumstances identified as conducive to cost-effective applications. With increasing applications, further research is recommended to better ascertain the circumstances under which this treatment is most or least beneficial to safety.

ACKNOWLEDGEMENT

This paper is based on a report prepared by Vanasse Hangen Brustlin, Inc (VHB) for the Federal Highway Administration, Office Safety under Contract DTFH61-05-D-00024. The FHWA project coordinator was Roya Amjadi who provided important guidance and administrative support. Other significant contributions to the study were made by Nancy Lefler, Robert Hoyle, Dr. Hugh McGee, Michelle Scism, and Joedel Zaballero, all of VHB and Dr. Aemal J. Khattak, Associate Professor, University of Nebraska-Lincoln. The project team gratefully acknowledges the participation of individuals in the following organizations for their assistance in this study: Broward County, Florida; Hillsborough County, Florida; The City of Daytona Beach, Florida; The City of Lincoln, Nebraska; The City of Omaha, Nebraska; The City of Tampa, Florida; The Florida Department of Transportation; The Nebraska Department of Roads; The University of Wisconsin; The Wisconsin Department of Transportation. Fundamental research was supported by a grant to the lead author from the Natural Sciences and Engineering Research Council of Canada.

REFERENCES

1. Antonucci, N. D., K. K. Hardy, K. L. Slack, R. Pfefer, and T. R. Neuman. *Guidance for Implementation of the AASHTO Strategic Highway Safety Plan: A guide for Reducing Collisions at Signalized Intersections*. NCHRP Report 500, Volume 1, Transportation Research Board, Washington, D.C., 2004.

2. Khattak, A. J., B. Naik, and V. Kannan. *Safety Evaluation of Left-Turn Lane Line Width at Intersections with Opposing Left-Turn Lanes.* Report for Project Number SPR-P1(03) P554, Nebraska Department of Roads, 2004.

3. Staplin, L., D. L. Harkey, K. H. Lococo, and M. S. Tarawneh. *Intersection Geometry design and Operational Guidelines for Older Drivers and Pedestrian, Volume I: Final Report*. Publication No. FHWA-RD-96-132, FHWA, U.S. Department of Transportation ,1997.

4. Potts, I., J. Stutts, R. Pfefer, T. R. Neuman, K. L. Slack, and K. K. Hardy. *Guidance for Implementation of the AASHTO Strategic Highway Safety Plan: A Guide for Reducing Collisions Involving Older Drivers*. NCHRP Report 500, Volume 9, Transportation Research Board, Washington, D.C., 2004.

5. Persaud, B., C. Lyon, K. Eccles, N. Lefler, and F. Gross. Safety Evaluation of Offset Improvements for Left-Turn Lanes. Publication FHWA-HRT-09-035, FHWA, U.S. Department of Transportation, 2009.
6. Hauer, E. *Observational Before-After Studies in Road Safety: Estimating the Effect of Highway and Traffic Engineering Measures on Road Safety*. Pergamon Press, Elsevier Science Ltd., Oxford, U.K., 1997.
7. *Notices.* Federal Register, Vol. 73, No. 20, Wednesday, January 30, 2008. http://www.whitehouse.gov/omb/fedreg/2008/013008_discountrate.pdf. Accessed June 25, 2008.
8. Council, F., E. Zaloshnja, T. Miller, and B. Persaud. (2005) *Crash Cost Estimates by Maximum Police-Reported Injury Severity Within Selected Crash Geometries*. Publication FHWA-HRT-05-051, FHWA, U.S. Department of Transportation, 2005.