Safety Effectiveness of Offsetting Opposing Left-Turn Lanes: A Case Study
Author(s): Bhaven Naik, Justice Appiah, Aemal J. Khattak, and Laurence R. Rilett
Source: *Journal of the Transportation Research Forum*, Vol. 48, No. 2 (Summer 2009), pp. 71-82
Published by: Transportation Research Forum
Stable URL: http://www.trforum.org/journal

Safety Effectiveness of Offsetting Opposing Left-Turn Lanes: A Case Study

by Bhaven Naik, Justice Appiah, Aemal J. Khattak, and Laurence R. Rilett

This paper discusses the benefits to intersection safety of offsetting left-turn lanes by widening the width of the lane-line marking between the left-turn lanes and their adjacent through lanes. The analysis was performed using an empirical Baye's procedure in order to account for potential bias due to regression-to-the-mean. Results from the analysis of 12 treated intersection approaches and 36 non-treated approaches in Lincoln, Nebraska, suggest statistically significant improvements in safety at the treated intersections.

INTRODUCTION

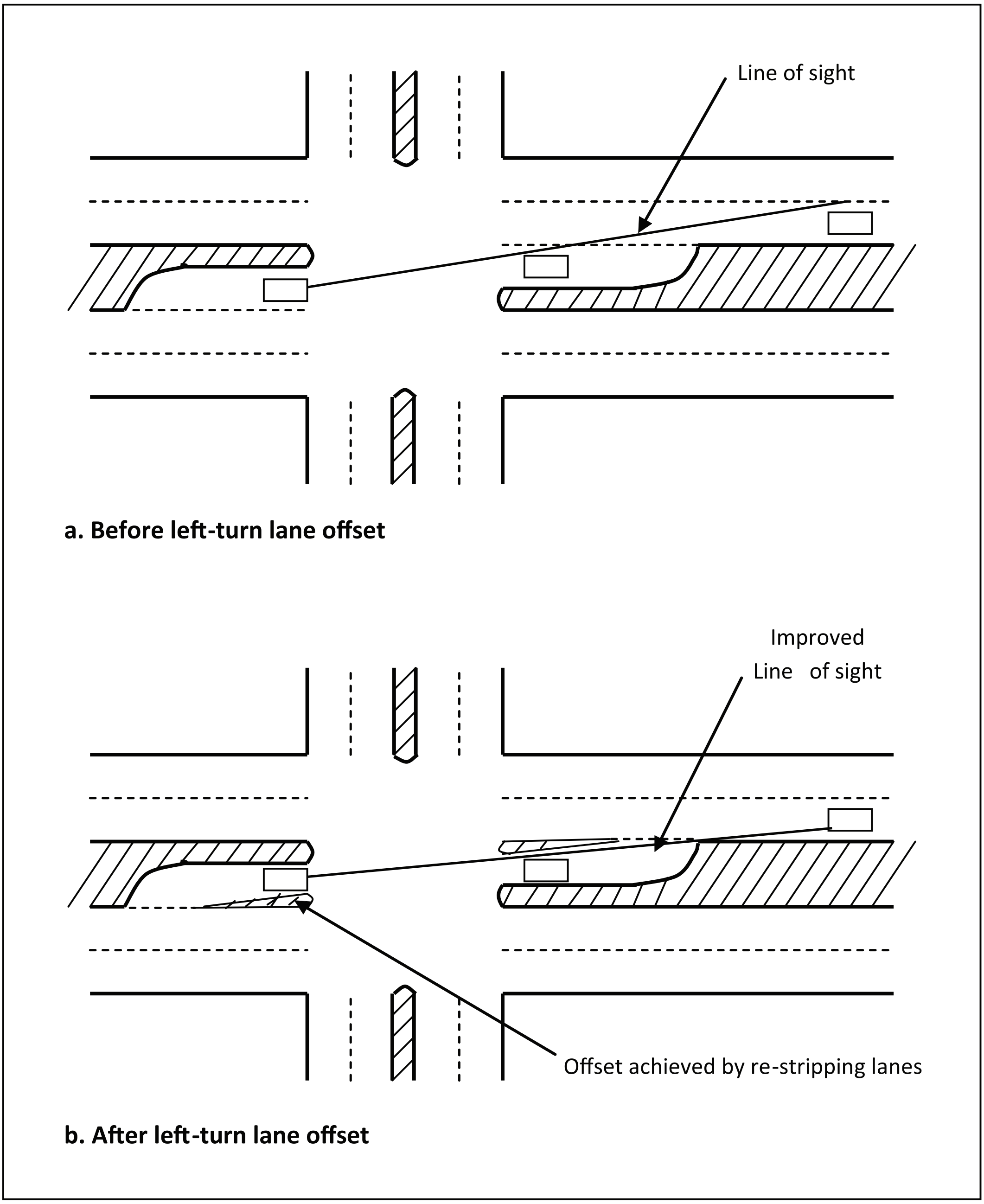
At signalized intersections, with heavy left-turning volumes, exclusive left-turn lanes serve to eliminate or at least to minimize potential conflicts between left-turning vehicles and through traffic. These lanes provide an area for the deceleration and storage of exiting vehicles so that through vehicles may continue without conflict and delay (McCoy et al. 1985). A recent study by the Federal Highway Administration (FHWA) reported that adding left-turn lanes reduced total crashes by 10 ± 0.8% and 35 ± 7.6% at urban and rural four-way signalized intersections, respectively (Harwood et al. 2002). A safety issue associated with left-turn lanes at most signalized intersections with permitted left-turn phasing is that vehicles in opposing left-turn lanes partially block each others' view of gaps in the oncoming through traffic through which they must turn (see Figure 1a). Crashes involving left-turning vehicles and opposing traffic account for 27.3% of all intersection-related crashes in the United States (O'Connor 2004). One solution to this problem is to offset the opposing left-turn lanes relative to each other as illustrated in Figure 1b. This improves the sight distance for left-turning drivers and aids with the identification of gaps in the oncoming traffic.

A review of the American Association for State Highway and Transportation Officials' (AASHTO) *A Policy on Geometric Design of Highways and Streets* (2001) indicates that the provision of adequate sight distance at signalized intersections with opposing left-turn lanes is desirable, and it suggests the use of parallel or tapered offsets as a means to provide improved visibility of opposing through traffic. However, it does not have any recommendations on the amount of offset. Guidelines to provide adequate sight distance for permitted left-turn movements at signalized intersections with opposing left-turn traffic were developed by (McCoy et al. 1992). These guidelines focused on the minimum offsets required to provide adequate sight distance to left-turning vehicles positioned at the stop line while being opposed by left-turn vehicles positioned within the intersection. The study indicated that minimum offsets of 2 ft (0.6 m) and 3.5 ft (1.1 m) are required to provide unrestricted sight distances to passenger cars and trucks, respectively, for design speeds up to 70 mph (112 km/h). Correlations between the offset distance for opposing left-turn lanes and the available sight distance for left-turning traffic have been reported (Joshua and Saka 1992).

Implementation of these guidelines involves reconstruction of the left-turn lanes at existing signalized intersections. However, the relatively high cost of reconstruction often prohibits, or at least delays, their implementation at such intersections. A relatively low cost option is to offset opposing left-turning vehicles by widening the width of the lane-line marking between the left-turn lanes and their adjacent through lanes as shown in Figure 1b. In other words, widen the lane striping such that the lane width is tapered more and, as such, encourages left-turning vehicles to move closer to the median, hence, improving sight distance. McCoy et al. (1999) studied driver response to lane-line widening at six signalized intersections in the cities of Lincoln and Omaha, Nebraska. The research demonstrated that vehicles in opposing left-turn lanes positioned themselves closer to the median when wider lane lines were used, thus, achieving adequate sight distances. The study also proposed guidelines for determining minimum left-turn lane-line widths required to provide adequate sight distances.

Although widening the lane-line marking would increase the available sight distance for left-turning vehicles and would intuitively seem to help reduce left-turn related crashes, empirical evidence of the safety impact is lacking. Bonneson et al. (1993) reported that one-third substantive

Figure 1: Effect of Offsetting Opposing Left-Turning Vehicles on Sight Distance



research exists to assess the safety impacts. Without any knowledge of the safety benefits of offsetting opposing left-turn lanes at signalized intersections, the continuation of this practice is somewhat questionable. The objective of this study was to conduct an exploratory assessment of the safety impacts as a result of implementing a low cost strategy (widening the lane-line marking) to offset opposing left-turn lanes at signalized intersections. A simple comparison of crash frequencies between "before" and "after" periods is not appropriate for analyzing safety impacts as safety invariably changes with time (Hauer 1997, 1983, 1980). For example, it cannot be assumed that had a treatment not been applied, safety in the "after" period would have been the same as in the "before" period. An approach based on empirical Bayesian methods has emerged as a better method of estimating safety compared with a simple before-after (B-A) study. This procedure was adopted for analysis and described in detail below.

EMPIRICAL BAYES PROCEDURE

The empirical-Bayes (E-B) procedure accounts for the effects of the regression-to-mean (RTM) in B-A safety studies (Hauer 1997, 1983). This is a systematic bias, which exists when the crash history of an entity (e.g., an intersection) had something to do with the decision to administer some treatment (e.g., offsetting of opposing left-turn lanes). Moreover, sites with potential for improvement are usually chosen based on their recent poor safety record (as was the case in this study), resulting in RTM bias; this is a situation where the count of crashes in the "after" period will generally revert toward the expected mean value even if the site was not treated (Washington et al. 2003, Abbess et al. 1981, Hauer and Persaud 1983). This can overstate the effect of a treatment by 5% to 10%, depending on the length of the "before" period (Sayed et al. 1998, Econometric Analysis 2004).

The basic concept of a B-A study as described by Hauer (1997) indicates assessing the expected change in safety at a treated intersection approach for a given crash type by:

(1) $\delta = \pi - \lambda$

where π is the expected number of crashes that would have occurred in the "after" period had the treatment not been applied, and λ is the expected number of crashes in the "after" period with the treatment in place.

In this study, the observed crash counts in the "after" period (*L*) were used as an estimate of both the expected number of crashes in the "after" period (λ) and its variance (assuming a Poisson distribution of crash counts). To predict the expected number of crashes in the "after" period without treatment (π) a multivariate regression model was developed. This model depicts the relationship between crash frequency and fundamental intersection features (such as traffic volumes) in a reference population of similar intersections over the entire study period (i.e., both before and after treatment). The estimated number of crashes in the reference population, κ, (regression estimate) was then combined with the reported number of crashes, K, at the study sites in the *n* years before treatment to obtain the long-term average (corrected for the RTM bias) of the expected number of crashes, $E(\kappa/K)$, at the study sites before treatment using the relationship:

(2) $E(\kappa/K) = \alpha E(\kappa) + (1 - \alpha)K$

where α ($0 \leq \alpha \leq 1$) is a parameter estimated from the mean and variance of κ as:

(3) $\alpha = \dfrac{E(\kappa)}{E(\kappa) + r\,var(\kappa)}$

and r is the ratio of the number of years to which K pertains to the number of years to which κ pertains (Hauer 1997). The variance of the expected number of crashes at the study sites before treatment was then determined as:

(4) $var\ (\kappa/\mathrm{K}) = (1 - \alpha)\ \mathrm{E}\ (\kappa/\mathrm{K})$

Relevant adjustment factors accounting for (1) differences in the lengths of the "before" and "after" periods (r_d) as well as (2) differences in traffic volumes (r_{tf}) were then applied to the estimate of the expected number of crashes, E(κ/K), at the study sites before treatment to yield an estimate of the number of crashes that would have occurred in the "after" period had the treatment not been applied, π.

The overall reduction in the expected number of crashes, δ, was then calculated as the difference between the sums of the πs and λs for all sites in the treatment group.

DATA

In June 1999, the City of Lincoln, Nebraska, in cooperation with the Nebraska Department of Roads (NDOR), offset opposing left-turn lanes at three select signalized intersections on urban arterial streets by widening the lane lines between the left-turn lanes and their adjacent through lanes. Figure 2 shows the lane-line widening, using two lane stripes, as applied to one of the study intersections. The data set used in this study was from three intersections, which were four-legged, right-angled, and signalized with protected/permitted left-turn signal phasing. However, there were some minor variations among the intersections in terms of lane widths, median type and width, and left-turn offset distance as summarized in Table 1.

Figure 2: Lane-Line Widening at SB Approach on 70th Street and Van Dorn Street

Before Widening After Widening

Table 1: Characteristics of Intersections

Intersection	Width of Left-Turn Lane Line (ft)		Width of Left-Turn (ft)		Median Separation	
	Before	After	Before	After	Type	Width (ft)
70th St. & Van Dorn St.	0.3	3.0	14.0	11.0	Paint	1.0
70th St. & O St.	0.3	1.3	11.3	10.3	Curb	5.0
48th St. & O St.	0.3	1.5	12.0	10.8	Curb	4.0

Source: Engineering Services Dept. – City of Lincoln

The six specific approaches under study at the three intersections were (See Figure 3 for a location map):

- North and South bound approaches on 70th Street and Van Dorn Street,
- East and West bound approaches on 70th Street and US-34 ("O" Street), and
- East and West bound approaches on 48th Street and US-34 ("O" Street).

For each site, crash data were obtained for a nine-year period beginning January 1, 1994, to December 31, 2003, of which 5.5 years pertained to the period before treatment application (i.e., offsetting of opposing left-turn lanes) and 3.5 years to the period after the treatment. The lengths of the before and after period were selected in accordance with available crash data. Data were extracted from summary crash records obtained from the Criminal Justice Information System database through the Engineering Services Department at the City of Lincoln. Crashes were considered pertinent if they involved left-turning and opposing through vehicles that were traversing the treated approaches. A total of 139 crashes satisfied this criterion. Attributes obtained from the crash records included date of occurrence, pavement condition, number and type of vehicles involved, visibility conditions, and injury severity. Traffic volume data collected at each intersection included the average daily traffic (ADT) on the major/treated approaches for each year during the study period. Table 2 summarizes the crash counts as well as the ADTs and the corresponding coefficients of variation for the study sites over the nine-year period. Traffic volume and crash data from 36 approaches on 10 other

Figure 3: Location Map of Intersections Under Study

Note: *Black spots indicate the study intersection
Source: http://maps.google.com

intersections (not treated) with similar characteristics as the treated intersections (i.e. four-legged, right-angled, and signalized intersections with protected/permitted left-turn signal phasing) were also collected and used as the reference population needed for the empirical Bayes procedure.

Table 2: Crash Frequency and ADT Statistics for the Study Sites

Intersection Approach	'Before' Period (5.5 years)			'After' Period (3.5 years)		
	Crash Count	ADT		Crash Count	ADT	
		Estimate*	Coefficient of Variation		Estimate*	Coefficient of Variation
NB 70 & Van Dorn	3	11102.3	0.028	1	12053.6	0.047
SB 70 & Van Dorn	10	12600.0	0.025	6	13000.0	0.000
EB 70 &O	9	16022.7	0.013	4	17900.0	0.090
WB 70 & O	21	11468.2	0.049	11	12135.7	0.007
EB 48 & O	29	20786.4	0.023	22	20850.0	0.000
WB 48 & O	14	18045.5	0.015	9	17982.9	0.012

Note: * Indicates the periodic (5.5 or 3.5 years) mean of the approach annual average daily traffic.
Source: Engineering Services Dept. - City of Lincoln

ANALYSIS

Data analysis was based on formulae and relevant theory as presented by Hauer (1997). The following text provides an account of the data analysis.

Estimating the Expected Number of Crashes in the "After" Period with Treatment, λ
As shown in Table 1, a total of 53 crashes were reported in the 3.5 years following treatment. This provided an estimate of both λ and its variance. Thus,

λ = 53 crashes and $var(\lambda)$ = 53 crashes^2

Estimating the Expected Number of Crashes in the "After" Period with No Treatment, π

The first step in estimating π was to estimate κ, the number of crashes that would be expected at intersection approaches with traffic volumes and other characteristics similar to the study sites (i.e., reference population).

Estimating the Expected Number of Crashes in the Reference Population, κ

A negative binomial model of the form given in equation 5 was formulated to estimate the expected number of crashes in the reference population.

(5) $E(\kappa) = bX^{\beta}Y^{\gamma}$

where,
X = ADT on the subject approach (i.e., approach under study)
Y = ADT on the opposing approach
b, β, and γ are unknown model parameters

The parameters b, β, and γ were estimated using the LIMDEP 8.0 software (Econometric Analysis 2004) as $e^{-11.76}$, 0.89, and 0.41, respectively. The parameter estimates suggest that a 1.0% increase in subject approach ADT results in a 0.89% increase in the expected number of crashes, while a 1% increase in the opposing approach ADT results in a 0.41% increase in the expected number of crashes.

The goodness-of-fit statistic, ρ^2, for the estimated model was 0.05, indicating a poor fit (ρ^2 varies between 0 and 1 with values closer to 1, indicating a good fit). However, the model was statistically significant overall (at 5% significance level) based on the $\chi 2$ statistic (p-value = 0.00). All coefficient estimates were statistically significant (p-value < 0.05). The dispersion parameter, α, was also significant (p-value = 0.00), indicating that the negative binomial model was appropriate for the dataset. Moreover, the negative binomial distribution is now regarded as being more appropriate to describe the count of crashes in a population of entities than the Poisson or normal distributions assumed in conventional regression modeling (Persaud et al. 2001).

For each of the m (36) approaches used in model fitting, the variance was estimated as the difference between the square of the residual and the estimate of κ obtained from equation 5. It should be noted that the variance, var(κ) might also be related to the covariates X and Y by some regularities that can be captured by a model, just as the mean E(κ) is (Hauer 1997). To capture this relationship, a model of the form shown in equation 6 was specified. This model expressed var(κ) as a function of E(κ) which had already been expressed as a function of the covariates X and Y in equation 5.

$$(6)\quad var(\kappa) = a_0 + a_1 \{E(\kappa)\}^2$$

where, a_0 and a_1 are unknown model parameters.

The model parameters, a_0 and a_1, were estimated using the SPSS 11.0 software as 2.0 and 0.6, respectively (Green et al. 2000). All coefficient estimates for the above model were statistically significant (at 5% significance level). Even though the R^2 value was low (0.05), E(κ) reliably predicted var(κ) as indicated by the F-value (F = 6.68, p-value = 0.011).

Estimating the Expected Number of Crashes at the Study Sites, E(κ/K), Before Treatment

As noted earlier, the estimated number of crashes in the reference population, E(κ), obtained from equation 5 was combined with the reported number of crashes, K, at the study sites in the 5.5 years before treatment to obtain the expected number of crashes at the study sites before treatment, E(κ/K), using equation 2. The methodology is illustrated using crash data for the northbound approach on the intersection of 70th Street and Van Dorn Street. The ADT on this approach was 11,102 vehicles/day while the opposing (i.e. southbound) approach ADT was 12,600 vehicles/day. Thus, using equation 5,

$E(\kappa) = e^{-11.76} (11102)^{0.89} (12600)^{0.41} = 1.5$ crashes/year and from equation 6 the variance is,

$var(\kappa) = 2.0 + 0.6 \times 1.5^2 = 3.4$ crashes^2/year^2

Then using equation 3, the parameter, α was estimated as,

$$\alpha = \frac{1.5}{1.5 = \left(\frac{5.5}{1.0}\right)(3.4)} = 0.075$$

Using equation 2 the expected number of crashes E(κ/K) is estimated as,

$E(\kappa / K) = 0.075 \times 1.5 + 3(1 - 0.075) = 28.9$ crashes with variance (equation 4),

$\mathrm{var}(\kappa / K) = 2.89(1 - 0.075) = 2.67$ crashes^2

Adjusting for Differences in Duration and Traffic Volumes

To estimate the expected number of crashes in the "after" period had the treatment not been applied, π, it is essential to consider the duration of the after period and differences in the ADTs between the "before" and "after" periods. This was accomplished by (1) first multiplying the expected number of crashes in the before period by r_d, the ratio of the duration of the "after" period to the duration of the "before" period and then by (2) r_{tf}, the ratio of the ADT during the "after" period to the ADT during the "before" period. Thus,

(7) $\pi = r_{tf} r_d \mathrm{E}\,(\kappa / K)$

As an example, recall the number of crashes on the northbound approach at the intersection of 70th Street and Van Dorn Street was estimated as 2.89 crashes (over the 5.5 year "before" period). The ADTs on this approach during the "after" and "before" periods were 12,053 and 11,102 vehicles/day, respectively. Hence,

$r_d = 3.5/5.5 = 0.636$, and $r_{tf} = 12053/11102 = 1.086$

which gives,

$\pi = 0.636 \times 1.086 \times 2.89 = 2.0$ crashes

This suggests that it is more likely that two crashes would have occurred in the "after" period had the treatment not been applied instead of the one crash which was actually observed. The variance of π was obtained as (8)

(8) $var(\pi) = r_d^2 \{ r_{tf}^2 \mathrm{E}(\kappa/\mathrm{K}) + [\mathrm{E}(\kappa/\mathrm{K})]^2 r_{tf}^2 (v_B^2 + r_A^2) \}$

where v_B and v_A are the coefficients of variation for the ADT estimates in the "before" and "after" periods, respectively (See Table 2 for coefficients of variation). Thus,

$\mathrm{var}(\pi) = 0.636^2 \{1.086^2 \times 2.89 + 2.89^2 \times 1.086^2 (0.028^2 + 0.047^2)\} = 1.39$ crashes^2

Table 3 provides a summary of the estimated and actual number of crashes for each of the study sites as computed using the procedures described above.

ESTIMATION OF SAFETY EFFECT

Two measures of effectiveness, (1) reduction in expected number of crashes and (2) index of effectiveness, were used to quantify the safety effect of offsetting left-turn movements at intersections using lane line widening.

Table 3: Estimating π with the Multivariate Regression Method

Intersection Approach	K	L (= λ)	E(κ/K)	π	var(κ/K)	var(π)
NB 70 & Van Dorn	3	1	2.89	2.00	2.67	1.39
SB 70 & Van Dorn	10	6	9.36	6.15	8.65	4.06
EB 70 &O	9	4	8.47	6.02	7.83	4.58
WB 70 & O	21	11	19.53	13.15	18.03	9.27
EB 48 & O	29	22	27.26	17.40	25.43	11.27
WB 48 & O	14	9	13.23	8.39	12.32	5.35
Total		53		53.11		35.92

Where,
K = observed/reported number of crashes before treatment was implemented
L = observed/reported number of crashes after treatment was implemented
E(κ/K) = expected number of crashes before treatment was implemented
π = expected number of crashes that would have occurred in the "after" period without treatment
var(κ/K) = variance of expected number of crashes before treatment was implemented
var(π) = variance of expected number of crashes that would have occurred in the "after" period without treatment

Reduction in Expected Number of Crashes

The reduction in expected number of crashes, δ, and its variance were obtained as:

$$\delta = \sum_{\text{all sites}} \pi - \sum_{\text{all sites}} \lambda = 53.11 - 53 = 0.11 \text{ crashes}$$

$$\text{var}(\delta) = \sum_{\text{all sites}} \text{var}(\pi) = \sum_{\text{all sites}} \text{var}(\lambda) = 35.92 + 53 = 88.92 \text{ crashes}^2$$

Index of Effectiveness

The index of effectiveness, *θ*, is approximately equal to the ratio of the number of crashes occurring after treatment to the number expected had treatment not been in place. It should be noted that $\theta <$ 1.0 indicates treatment was effective, $\theta >$ 1.0 indicates treatment was harmful to safety, and $\theta = 1.0$ indicates treatment did not affect safety. Unbiased estimates of θ and its variance were estimated as Hauer (1997):

(9) $$\theta = \frac{\lambda}{\{1+var(\ )/\ ^2\}}$$

= (53/53.11)/[1 + 35.92/53.11²] = 0.985, and

(10) $$var\{\theta\} = \frac{\theta^2\{var(\lambda)/\lambda^2 + var(\ )/\ ^2\}}{\{1+var(\ )/\ ^2\}^2}$$

$$= \frac{0.9852\ (53/53^2 + 35.92/53.11^2)}{(1 + 35.92/53.11^2)^2} = 0.029$$

The estimate of θ suggests that the treatment was only marginally effective at improving safety at the treated intersections. On average, the number of crashes occurring after treatment was 0.985 times the number expected had the treatment not been applied. This is equivalent to a 1.5% reduction in crashes.

CONCLUSIONS

Research by McCoy et al. (1999) demonstrated that by widening the lane striping at left-turn lanes the lane width is tapered more and left-turning vehicles positioned themselves closer to the median, thus, improving their sight distance. Most research in this area has been concerned with the development of guidelines for designing offset left-turn lanes, and even though one-third of state highway departments have successfully implemented widened lane-line markings, any empirical evidence of safety benefits is lacking. Highway safety literature shows that the empirical Bayes procedure is more appropriate for a before-after analysis of safety assessment when sites are chosen based on their past safety record. The appropriateness stems from the fact that the procedure accounts for the regression-to-mean bias.

This paper presents exploratory results on the safety changes attained as a result of implementing a low cost strategy (widening lane-line markings) to offset opposing left-turn lanes at six signalized intersections in Lincoln, Nebraska. Empirical Bayes procedure utilizing the multivariate regression method was employed to account for effects of regression to mean and differences in traffic volumes between the "before" and "after" periods.

The estimate of safety effectiveness, θ, for the three intersections was 0.79, 0.75, and 1.17. This indicated improvements in safety at two of the study intersections (70th Street & Van Dorn Street and 70th Street & 'O' Street) and a deterioration in safety at the 48th Street & 'O' Street intersection. Overall, the estimate of safety effectiveness indicated a 1.5% improvement in safety with a standard deviation of 0.173. The result was considered reliable since its standard deviation is more than two to three times smaller than the estimate as explained by Hauer (1997). Thus, this case study shows that the method of offsetting opposing left-turns lanes by lane-line widening has potential for improving intersection safety. Furthermore, lane-line widening is obviously a cheaper option.

It is important to mention that only crashes involving vehicles exiting intersections from left-turn lanes and those entering from the opposing approach were considered in this study. The effects of offsetting opposing left-turn lanes at signalized intersections on other crash types is recommended so as to obtain a better assessment of overall intersection safety. The authors also recommend a study that involves a larger database and one that incorporates other variables, such as lane widths.

Acknowledgements

The contents of this paper reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. This paper was a result of research conducted at the Mid-America Transportation Center, University of Nebraska-Lincoln. The authors gratefully acknowledge the contributions of numerous individuals and organizations that made the successful completion of this research possible.

References

Abbess, C., D. Jarrett, and C.C. Wright. "Accidents at Blackspots: Estimating the Effectiveness of Remedial Treatment with Special Reference to the "Regression to Mean" Effect." *Traffic Engineering and Control* 22 (10), (1981): 535-542.

American Association of State Highway and Transportation Officials. *A Policy on Geometric Design of Highways and Streets*. AASHTO, Washington D.C., 2001.

Bonneson, J., P.T. McCoy, and J. Truby. "Safety Improvements at Intersections on Rural Expressways: A Survey of State Departments of Transportation." *Transportation Research Record: Journal of the Transportation Research Board* 1385, (1993): 41-47.

Econometric Analysis Inc. *LIMDEP 8.0 Version User Manual*. http://www.limdep.com. (Accessed September 8, 2004)

Green, S.B., N.J. Salkind, and T.M. Akey. *Using SPSS for Windows: Analyzing and Understanding Data.* Prentice Hall, Upper Saddle River, New Jersey, 2000.

Harwood, D.W., K.M. Bauer, I.B. Potts, D.J. Torbic, K.R. Richard, E.R. Kohlman, R. Abbani, E. Hauer, and L. Elefteriadou. *Safety Effectiveness of Intersection Left- and Right-Turn Lanes*. Final Report, FHWA-RD-02-089, Federal Highway Administration, Virginia, July 2002.

Hauer, E. *Observational B-A Studies in Road Safety*. Pergamon, Elsevier Science Inc., Tarrytown, New York, 1997.

Hauer, E. "Reflections on Methods of Statistical Inference in Research on the Effect of Safety Countermeasures." *Accident Analysis and Prevention* 4, (1983): 275-285.

Hauer, E. and B.N. Persaud. "A Common Bias in Before and After Accident Comparisons and its Elimination." *Transportation Research Record: Journal of the Transportation Research Board* 905, (1983): 164-174.

Hauer, E. "Selection for Treatment as a Source of Bias in Before and After Studies." *Traffic Engineering and Control* 8/9, (1980): 419-421.

Joshua, S.C. and A.A. Saka. "Mitigation of Sight Distance Problem for Unprotected Left-turning Traffic at Intersections." *Transportation Research Record: Journal of the Transportation Research Board* 1356, (1992): 73-79.

McCoy, P.T., P.S. Byrd, and G. Pesti. *Pavement Markings to Improve Opposing Left-turn Lane Sight Distance*. Final Report, NDOR Project No. STPP-STWD (36), City of Lincoln Project No. 700791, Nebraska, September 1999.

McCoy, P.T., U.R. Navarro, and W.E. Witt. "Guidelines for Offsetting Opposing Left-turn Lanes on Four-lane Divided Roadways." *Transportation Research Record: Journal of the Transportation Research Board* 1356, (1992): 28-36.

McCoy, P.T., W.J. Hoppe, and D.V. Dvorak. "Benefit-Cost Evaluation of Left-Turn Lanes on Uncontrolled Approaches of Rural Intersections." *Transportation Research Record: Journal of the Transportation Research Board* 1026, (1985): 40-43.

O'Connor, T. Intersection Collision Avoidance. http://www.calccit.org/itsdecision/serv_and_tech/Collision_avoidance/intersection.html. (Accessed May 12, 2005).

Persaud, B.N., R.A. Retting, P. Garder, and D. Lord. "Safety Effect of Roundabout Conversions in the U.S.: Empirical Bayes Observational Before-After Study." *Transportation Research Record: Journal of the Transportation Research Board* 1757, (2001): 1-8.

Sayed, T., W. Abdelwahab, and J. Nepomuceno. "Safety Evaluation of Alternative Signal Head Design." *Transportation Research Record: Journal of the Transportation Research Board* 1635, (1998): 140-146.

Washington S., M. Karlaftis, and F. Mannering. *Statistical and Econometric Methods for Transportation Data Analysis*. Chapman and Hall/CRC, Boca Raton, Florida, 2003.

Bhaven Naik *is a Ph.D. candidate in the Transportation Systems Analysis program at the University of Nebraska-Lincoln. His research interests are in transportation infrastructure, planning and safety, traffic simulation modeling, and intelligent transportation systems. Bhaven holds B.S. and M.S. degrees in Civil Engineering from the University of Nebraska- Lincoln.*

Justice Appiah *is a Ph.D. candidate in the Transportation Systems Analysis program at the University of Nebraska-Lincoln. His research interests are in transportation network modeling and simulation and discrete choice analysis. Justice holds B.S. and M.S. degrees in Civil Engineering from the University of Science and Technology, Ghana, and Texas A&M University, College Station, respectively.*

Aemal J. Khattak *is an associate professor of Civil Engineering at the University of Nebraska-Lincoln. Khattak specializes in Transportation infrastructure, planning and safety, geographic information systems, and intelligent transportation systems. He has authored or co-authored more than 30 refereed journal papers and conference papers.*

Laurence R. Rilett *is a professor of Civil Engineering and the Director of the Mid-America Transportation Center at the University of Nebraska-Lincoln. Rilett specializes in multimodal transportation systems analysis, transportation planning and operations, dynamic network modeling and optimization, and Intelligent Transportation Systems applications. He has been a principal investigator or co-principal investigator on more than 20 research projects and has authored or co-authored more than 90 refereed journal papers and conference papers. He serves as associate editor for the ASCE Journal of Transportation Engineering.*