Offsetting Opposing Left-Turn Lanes at Signalized Intersections: A Safety Assessment Case Study in Lincoln, Nebraska

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ABSTRACT
Opposing left-turning vehicles at signalized intersections block each others' view of oncoming traffic. The ability to see oncoming traffic is critical for safe negotiation of left-turns at intersections during a permitted left-turn phase of the signal. Offsetting of opposing left-turn lanes at signalized intersections improves sight distance for left-turning motorists. This paper reports on a case study conducted in the City of Lincoln, Nebraska that was aimed at analyzing the safety benefits from offsetting opposing left-turn lanes at signalized intersections. Data from before-after scenarios were analyzed using the empirical Bayes procedure, which accounts for the effects of regression to the mean. The multivariate regression method was used to estimate the expected number of crashes for a reference population of 36 non-treated intersection approaches with similar geometric and traffic characteristics as the treated sites. These estimates were then used to determine the expected number of crashes at the treated sites in the 'after' period, had the treatment not been applied.

Results from this study indicate a 1.5 percent change in safety. Based on the results, the author concludes that safety improved (but only minimally) at the three treated intersections as a result of offsetting opposing left-turn lanes.

INTRODUCTION

Left-turn lanes at signalized intersections are provided to minimize interference that a turning vehicle may have on 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 (*1*). A recent study by the Federal Highway Authority (FHWA) reported that adding left-turn lanes reduced total accidents by 10 ± 0.8 percent and 35 ± 7.6 percent at urban and rural four-way signalized intersections respectively *(2)*. A safety issue associated with left-turn lanes at signalized intersections with permitted left-turn phase is that vehicles in opposing left-turn lanes obstruct each others' view of oncoming through traffic through which they must turn (see Figure 1a). Crashes involving left-turning vehicles and opposing traffic account for 27.3 percent of all intersection-related crashes in the United States (*3*). Offsetting the opposing left-turn lanes relative to each other improves sight distance (Figure 1 b) for left-turning drivers that aids with 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* (*4*) 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 of providing improved visibility of opposing through traffic. However, it does not specify the amount of offset required. 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*. (*5*)*.* 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). Strong correlations between the offset distance for opposing left-turn lanes and the available sight distance for left-turning traffic have been reported by Joshua and Saka (*6*).

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, the elimination of sight distance problems at such intersections. A relatively inexpensive option is to offset opposing left turning vehicles by widening the lane lines between left-turn lanes and adjacent through lanes (Figure 1b). To evaluate the effectiveness of lane line widening on improving sight distances, McCoy *et al*. (*7*) studied driver response to lane line widening at six signalized intersections in the cities of Lincoln and Omaha, Nebraska. The available sight distances were compared to the required sight distances to determine the percentage of left-turning vehicles with adequate sight distance (i.e., available sight distance greater than or equal to the required sight distance). 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 increasing the available sight distance for left-turning vehicles would intuitively seem to help reduce left-turn related crashes, empirical evidence of the safety impact of offsetting opposing left-turn lanes is lacking. Bonneson *et al*.(*8*) reported that one-third of all state highway departments have successfully used the offset left-turn design at selected locations but no substantive research exists to assess the safety impacts. Without concrete 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 assess empirical evidence of safety impacts as a result of offsetting 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 (*9, 10, 11*). One therefore, cannot assume 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 to a simple before-after (B-A) study. This procedure was adopted for analysis and described in detail next.

EMPIRICAL BAYES PROCEDURE

The empirical-Bayes (E-B) procedure was formulated by Hauer and employed to account for the effects of the regression-to-mean in B-A safety studies (*9, 11*). 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 regression-to-mean bias; a situation where the count of crashes in the 'after' period will generally revert towards the expected mean value even if the site was not treated (*12, 13*). This can overstate the effect of a treatment by 5 to 10 percent, depending on the length of the 'before' period.

The basic concept of a B-A study as described by Hauer *(9)* indicates assessing the expected change in safety at a treated intersection approach for a given crash type by:

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

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).

The observed crash counts in the 'after' period; L are 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). However, Hauer (*14*) argues that in conducting B-A safety studies, it is the method of predicting the expected number of crashes in the 'after' period without treatment (π) that is important. Two such methods are available; i) the method of sample moments, which is simple and rarely used and ii) the multivariate regression method, used when intersection features are continuous in nature. The latter method was used in this study.

The multivariate regression method pivots itself on the concept of a reference population. A model depicting the relationship between crash frequency and fundamental intersection features such as traffic volumes is developed from this reference population. The estimated value of κ (regression estimate) is then combined with the reported number of crashes, K in the n years before treatment to obtain an estimate of the expected number of crashes, E(κ/K) at the study sites before treatment using the relationship

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

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

$$\alpha = \frac{E(\kappa)}{E(\kappa) + r\,\mathrm{var}(\kappa)} \qquad (3)$$

and r is the ratio of the number of years to which K pertains to the number of years to which κ pertains (*8*).

The variance of expected number of crashes at the study sites before treatment is then determined as:

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

Relevant factors accounting for differences in the lengths of the 'before' and 'after' periods (r_d) as well as differences in traffic volumes (r_{tf}) are then applied to the estimate of the expected number of crashes, E(κ/K) at the study sites before treatment. The result is then an estimate of the number of crashes that would have occurred in the 'after' period without treatment (π). The overall reduction in the expected number of crashes, δ was then calculated as the difference between the sums of the π's and λ's 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 select signalized intersections on urban arterial streets by widening the lane lines between the left-turn lanes and their adjacent through lanes. 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 amongst the three in terms of lane widths, median type and width, and left-turn offset distance. The three study intersections were:

- 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 collected for 9 years, 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. 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 1 shows select statistics on crash frequencies and ADT for the study sites over the 9 year period. Traffic volume and crash data from 36 approaches on 10 other intersections (not treated) with similar characteristics as the treated intersections were also collected and used as the reference population, needed for the empirical Bayes procedure.

ANALYSIS

Data analysis was based on formulae and relevant theory as presented by Hauer (*9*). The following text provides an account of the data analysis.

Estimating λ (expected number of crashes in the 'after' period with treatment)

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,

$$\lambda = 53\ crashes$$

and

$$\text{var}(\lambda) = 53\ crashes^2$$

Estimating π (expected number of crashes in the 'after' period with no treatment)

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 κ:

With the multivariate regression method, a negative binomial regression model that related the expected number of crashes to traffic volumes both on the subject approach (approach under study) and the opposing approach was estimated as:

$$\text{E}(\kappa) = \text{e}^{-11.76}(\text{Approach ADT})^{0.89}(\text{Opposing ADT})^{0.41} \quad (5)$$

The ρ^2 value (a statistic indicating model fit) for the above model was 0.05, indicating a not-so-good fit (ρ^2 varies between 0 and 1 with values closer to 1 indicating a better fit). However, the model overall fit was statistically significant ($\alpha = 0.05$) 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 more reasonable than the Poisson regression model. The model was estimated using the LIMDEP 7.0 software (Econometric Software, Inc.).

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) above. This variance was then used to establish a linear regression model between var(κ) and E(κ) as:

$$\text{var}(\kappa) = 2.0 + 0.6\{E(\kappa)\}^2 \quad (6)$$

All coefficient estimates for the above model were statistically significant ($\alpha = 0.05$). 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).

For estimating the expected number of crashes, E(*κ/K*) at the study sites before treatment, the North Bound approach on the intersection of 70th street and Van Dorn street is used as an illustration. The subject approach and opposing approach ADTs before treatment were 11,102 and 12,600 vehicles/day, respectively. Thus using equation 5;

$$E(\kappa) = e^{-11.76}(11102.27)^{0.89}(12600)^{0.41} = 1.5 \text{ crashes/year}$$

And using equation 6;

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

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

$$\alpha = \frac{1.5}{1.5 + 5.5(3.4)} = 0.075$$

The expected number of crashes, E(κ/K) at this site before treatment and its variance were estimated using equation 2 as;

$$E(\kappa / K) = 0.075 \times 1.5 + 3(1 - 0.075) = 2.89 \text{ crashes}$$

And using equation 4;

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

Adjustments for Differences in Duration and Traffic Volumes

To finally estimate *π*, differences in durations and traffic volumes between the ‘before’ and ‘after’ periods were considered. This was accomplished by multiplying the expected number of crashes in the ‘before’ period by two ratios – (i) the ratio of ‘before’ period duration to ‘after’ period duration, r_d and (ii) the ratio of average traffic in the ‘after’ period to average traffic in the ‘before’ period, r_{tf}.

Continuing with the illustration using the North Bound approach at the intersection of 70th street and Van Dorn streets, the traffic and duration adjustment factors were estimated as 1.086 and 0.636, respectively. Thus,

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

$$= 1.086 \times 0.636 \times 2.89 = 2.0 \text{ crashes}$$

and

$$\text{var}(\pi) = r_d^{\,2}\{r_{tf}^{\,2} E(\kappa / K) + [E(\kappa / K)]^2 r_{tf}^{\,2}(v_B^{\,2} + v_A^{\,2})\} \tag{8}$$

where v_B and v_A are the coefficients of variation for the traffic estimates in the ‘before’ and ‘after’ periods, respectively. Thus,

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

Overall estimates for the parameters π and λ were obtained as the sum of the individual estimates for the treated sites (See Table 2).

Estimation of Safety Effect

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

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 being 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 (*9*):

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

$$= (53/53.11)/\left[1 + 35.92/53.11^2\right] = 0.985$$

and

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

$$= \frac{0.985^2(53/53^2 + 35.92/53.11^2)}{(1 + 35.92/53.11^2)^2} = 0.029$$

Typically, the index of effectiveness is expressed as a percentage crash reduction given by;

$$E = 100(1-\theta) \tag{11}$$

Table 3 summarizes the results of the analysis. It provides estimates of the two measures of effectiveness of safety treatment obtained.

CONCLUSIONS

Previous studies have shown that offsetting opposing left-turn lanes at signalized intersections increases sight distance for left-turning motorists. 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 installed them, 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 study assessed the change in safety that was attained by offsetting opposing left-turn lanes at three signalized intersections in Lincoln, Nebraska, using police-reported crash data spanning 9 years – 5.5 years before treatment and 3.5 years after treatment. 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 indicated a 1.5 percent change in safety with a standard deviation of 0.173. The result was considered as reliable since its standard deviation is more than two to three times smaller than the estimate as explained by Hauer (9). Thus this case study shows that safety improved (but only minimally) at the treated intersections due to the offsetting of opposing left-turns lanes by lane line widening. However, it should be noted that a marked improvement in safety could have been possible if a larger sample size was available.

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. It is also recommended that a study that involves a larger database and one that incorporates other variables, such as lane widths be conducted in the future.

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LIST OF TABLES AND FIGURES

TABLE 1 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

* Indicates the periodic (5 or 3.5 years) mean of the approach annual average daily traffic.

TABLE 2 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

TABLE 3 Summary Before-After Safety Parameters

Parameter		Multivariate Regression
λ	Estimate	53.00
	Variance	53.00
π	Estimate	53.11
	Variance	35.92
δ	Estimate	0.11
	Variance	88.92
θ	Estimate	0.985
	Variance	0.030

Where;

λ = expected number of crashes in the 'after' period with treatment implemented

π = expected number of crashes in the 'after' period without treatment being implemented

δ = reduction in expected number of crashes

θ = index of effectiveness

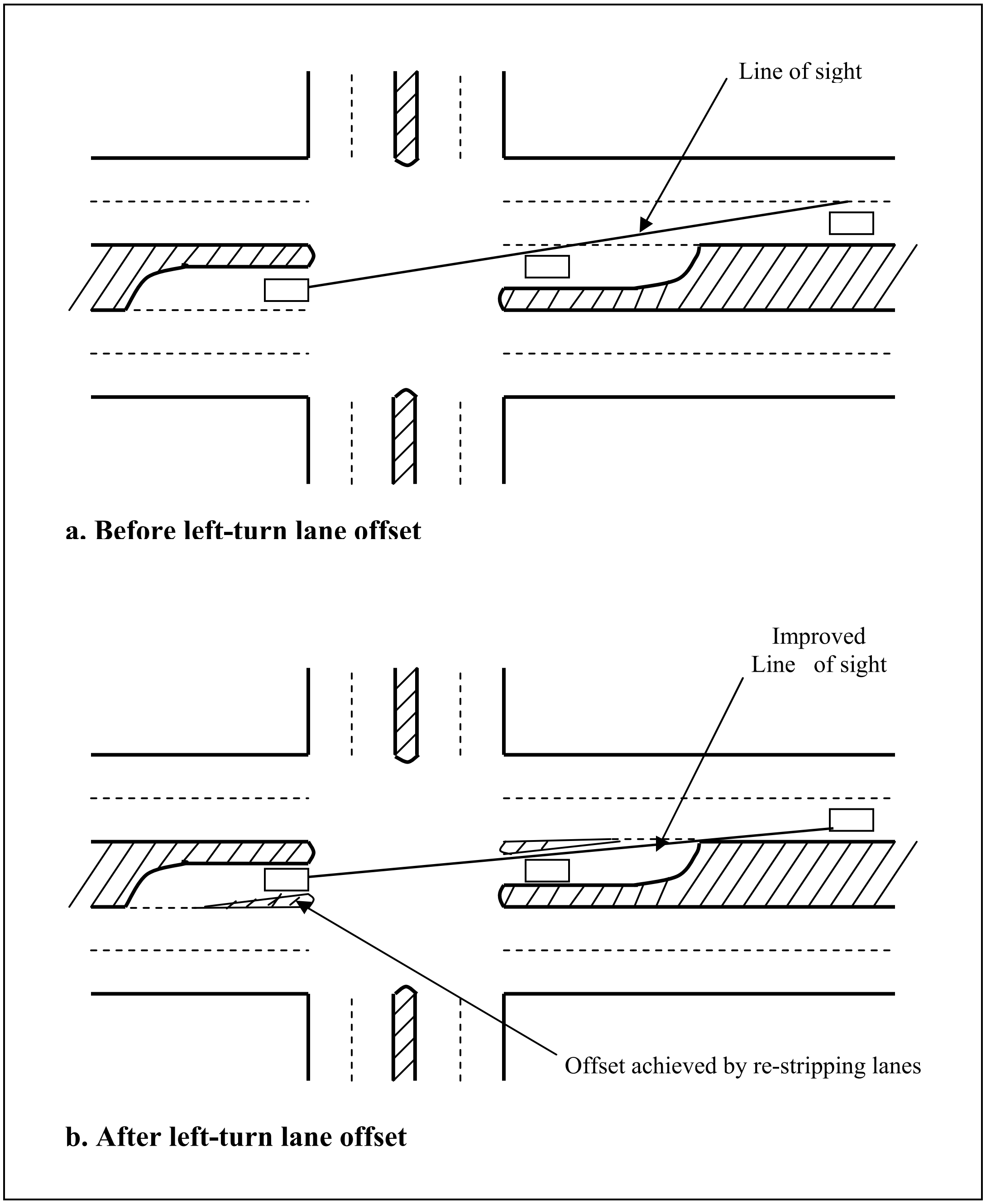

FIGURE 1 Effect of offsetting opposing left-turning vehicles on sight distance.