Crash Reductions Following Installation of Roundabouts in the United States

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ABSTRACT

Modern roundabouts are designed to control traffic flow at intersections without the use of stop signs or traffic signals. U.S. experience with modern roundabouts is rather limited to date, but in recent years there has been growing interest in their potential benefits and a relatively large increase in roundabout construction. The present study evaluated changes in motor vehicle crashes following conversion of 24 intersections from stop sign and traffic signal control to modern roundabouts. The settings, located in 8 states, were a mix of urban, suburban, and rural environments. A before-after study was conducted using the empirical Bayes approach, which accounts for regression to the mean. Overall, the empirical Bayes procedure estimated highly significant reductions of 39 percent for all crash severities combined and 76 percent for all injury crashes. Reductions in the numbers of fatal and incapacitating injury crashes were estimated to be about 90 percent. Overall, results are consistent with numerous international studies and suggest that roundabout installation should be strongly promoted as an effective safety treatment for intersections.

INTRODUCTION

The modern roundabout is a form of intersection traffic control that has become increasingly common around the world but is seldom used in the United States. Circular intersections are not a new idea and, in fact, predate the advent of the automobile. The first one-way rotary system for motor vehicle traffic in the United States was put into operation in 1905 at Columbus Circle in New York City (Todd, 1988).

The main difference between modern roundabouts and older circles/rotaries is the design speed. Older rotaries typically were built according to 1940s-era design standards or even older guidelines, which generally were intended for vehicle speeds of 25 mph or more. Drivers typically enter older traffic circles at speeds of 35 mph or more. In contrast, modern roundabouts are designed for very low traffic speeds, about 15 mph. The low design speed is accomplished through two primary design features: drivers must enter the roundabout facing a central island rather than tangentially (this feature is known as deflection), and the approaches to the roundabout are curved to promote low entry speeds. Common characteristics that define a modern roundabout and provide safety features are: drivers entering a roundabout must yield to vehicles within the circulatory roadway, keeping weaving to a minimum; roundabout entrances and exits are curved to promote low traffic speeds; traffic circulates counterclockwise, passing to the right of a central island; raised "splitter" islands dividing the roadway at entrances and exits provide refuge for pedestrians, ensure drivers travel in the intended path, and separate opposing traffic (Figure 1). In addition, pedestrian activities are prohibited on the central island, pedestrians are not intended to cross the circulatory roadway, and when pedestrian crossings are provided for approach roads they are placed approximately one car length back from the entry point.

Numerous studies, mostly in the international literature, indicate that modern roundabouts are safer than other methods of intersection traffic control, and that converting intersections from stop signs or traffic signals to roundabouts is associated with substantial reductions in motor vehicle crashes and injuries. For example, Schoon and van Minnen (1994) studied 181 Dutch intersections converted from conventional controls (traffic signals or stop signs) to modern roundabouts and reported that crashes and injuries were reduced by 47 and 71 percent, respectively; the more severe injury crashes (resulting in hospital admissions) were reduced by 81 percent. Troutbeck (1993) reported a 74 percent reduction in the rate of injury crashes following conversion of 73 roundabouts in Victoria, Australia. These and similar studies may overestimate the magnitude of crash reductions associated with conversion of intersections to roundabouts by failing to control for regression-to-the-mean effects — a major problem affecting the validity of many road safety improvement studies. A thorough review of the literature was conducted by Elvik et al. (1997), who concluded that converting from yield, two-way stop, or traffic signal control to a roundabout reduces the total number of injury crashes by 30-40 percent. Reductions in the number of

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Figure 1
Views of Roundabout in Cecil County, MD

pedestrian crashes were in the same range. Bicycle crashes were reduced by approximately 10-20 percent. It should be noted that the Elvik et al. study was a meta-analysis that included some circular intersections not meeting the typical definition of modern roundabouts. Regression to the mean was not controlled for.

U.S. experience with modern roundabouts is rather limited to date, but there has been growing interest in their potential benefits and, recently, a relatively large increase in roundabout construction. Garder (1997) conducted an extensive review of existing and planned U.S. installations and reported strong activity in several states including Colorado, Florida, Maine, Maryland, Michigan, Nevada, Vermont, and Washington. A recent, but limited, before-after crash study was conducted by Flannery and Elefteriadou (1999) based on 8 roundabouts, 3 in Florida and 5 in Maryland. Results were promising, suggesting consistent reductions in crashes and injuries, but the analyses were limited in scope.

The present before-after study was designed to better estimate the nature and magnitude of crash reductions following installation of modern roundabouts in the United States. It included a greater number of intersections and employed more powerful statistical analysis tools than the simple before-after comparisons used in prior studies.

METHOD

The empirical Bayes approach was employed to properly account for regression to the mean while normalizing for differences in traffic volume between the before and after periods. The change in safety at a converted intersection for a given crash type is given by:

$$B-A, \tag{1}$$

where B is the expected number of crashes that would have occurred in the after period without the conversion and A is the number of reported crashes in the after period.

To eliminate regression-to-the-mean effects and to reduce uncertainty in the results, B was, in general, estimated using an empirical Bayes procedure (Hauer, 1997) described more fully in the appendix. In essence, a regression model is used to first estimate the annual number of crashes (P) that would be expected at intersections with traffic volumes and other characteristics similar to the one being analyzed. The regression estimate is then combined with the count of crashes (x) in the n years before conversion to obtain an estimate of the expected *annual* number of crashes (m) at the intersection before conversion. This estimate of m is:

$$m = w_1(x) + w_2(P), \tag{2}$$

where the weights w_1 and w_2 are estimated from the mean and variance of the regression estimate as:

$$w_1 = P/(k + nP) \tag{3}$$

$$w_2 = k/(k + nP), \tag{4}$$

where

$$k = P^2/Var(P) \tag{5}$$

is a constant for a given model and is estimated from the regression calibration process.

Factors then are applied to account for the length of the after period and differences in traffic volumes between the before and after periods. The result is an estimate of B. The procedure also produces an estimate of the variance of B. The significance of the difference ($B-A$) is established from this estimate of the variance of B and assuming, based on a Poisson distribution of counts, that:

$$Var(A) = A. \tag{6}$$

Uncertainty in the estimates of safety effects also can be described with the use of likelihood functions, which have been presented in the full project report (Persaud et al., 1999).

ASSEMBLY OF DATA AND REGRESSION MODELS

Data for converted intersections: The analyses were confined to 8 states — California, Colorado, Florida, Kansas, Maine, Maryland, South Carolina, and Vermont — where a total of 24 intersections were converted to modern roundabouts between 1992 and 1997. There are a few modern roundabouts in the United States that are not included in the present analysis because data were not available or the roundabouts were too new.

Of the 24 intersections studied, 21 were previously controlled by stop signs, and 3 were controlled by traffic signals. Fifteen of the roundabouts were single-lane circulation designs, and 9, all in Colorado, were multilane. Summary data for the study intersections are given in Table 1. For each intersection, crash data were obtained for periods before and after conversion. The construction period, as well as the first month after completion, were excluded from analysis. The lengths of the before and after periods varied in accordance with available crash data. In no case was a period shorter than 15 months. Data were extracted from printed police crash reports and, where not available, from report summaries. Information regarding injuries also was derived from police crash reports. Police reports convey the detection and apparent severity of injuries, either through the so-called KABCO scale (Killed, A injury, B injury, C injury, Only property damage) or by separating injuries into three categories: possible injury, non-incapacitating injury, and the more severe incapacitating injuries. In this study, "possible" injuries were not counted as injuries. Injury data based on police reports have known limitations, especially in regard to injury severity. During the study period, there were no known changes in reporting practices that would cause a change in the number of reported crashes.

Table 1
Details of the Sample of Roundabout Conversions

								Crash Count			
	Year	Control	Single or	AADT		Months		Before		After	
Jurisdiction	Opened	Before*	Multilane	Before	After	Before	After	All	Injury	All	Injury
Anne Arundel County, MD	1995	1	Single	15,345	17,220	56	38	34	9	14	2
Avon, CO	1997	2	Multilane	18,942	30,418	22	19	12	0	3	0
Avon, CO	1997	2	Multilane	13,272	26,691	22	19	11	0	17	1
Avon, CO	1997	6	Multilane	22,030	31,525	22	19	44	4	44	1
Avon, CO	1997	1	Multilane	18,475	27,525	22	19	25	2	13	0
Avon, CO	1997	6	Multilane	18,795	31,476	22	19	48	4	18	0
Bradenton Beach, FL	1992	1	Single	17,000	17,000	36	63	5	0	1	0
Carroll County, MD	1996	1	Single	12,627	15,990	56	28	30	8	4	1
Cecil County, MD	1995	1	Single	7,654	9,293	56	40	20	12	10	1
Fort Walton Beach, FL	1994	2	Single	15,153	17,825	21	24	14	2	4	0
Gainesville, FL	1993	6	Single	5,322	5,322	48	60	4	1	11	3
Gorham, ME	1997	1	Single	11,934	12,205	40	15	20	2	4	0
Hilton Head, SC	1996	1	Single	13,300	16,900	36	46	48	15	9	0
Howard County, MD	1993	1	Single	7,650	8,500	56	68	40	10	14	1
Manchester, VT	1997	1	Single	13,972	15,500	66	31	2	0	1	1
Manhattan, KS	1997	1	Single	4,600	4,600	36	26	9	4	0	0
Montpelier, VT	1995	2	Single	12,627	11,010	29	40	3	1	1	1
Santa Barbara, CA	1992	3	Single	15,600	18,450	55	79	11	0	17	2
Vail, CO	1995	1	Multilane	15,300	17,000	36	47	16	n/a	14	2
Vail, CO	1995	4	Multilane	27,000	30,000	36	47	42	n/a	61	0
Vail, CO	1997	4	Multilane	18,000	20,000	36	21	18	n/a	8	0
Vail, CO	1997	4	Multilane	15,300	17,000	36	21	23	n/a	15	0
Washington County, MD	1996	1	Single	7,185	9,840	56	35	18	6	2	0
West Boca Raton, FL	1994	1	Single	13,469	13,469	31	49	4	1	7	0

*1 = four-legged, one street stopped; 2 = three-legged, one street stopped; 3 = all-way stop; 4 = other unsignalized; 6 = signal

Regression models: From data about intersections not converted and a consideration of existing models, the regression models required for the empirical Bayes estimates of safety effect (Equations 2-5) were assembled. New models were calibrated for stop controlled urban intersections, whereas other models were adopted from Lord (2000) for signalized intersections and Bonneson and McCoy (1993) for rural stop controlled intersections. For urban stop controlled intersections, two levels of models were calibrated:

$$\text{level 1: } \textit{crashes/year} = (\alpha)\ (\textit{total entering AADT})^{\beta} \tag{7}$$

$$\text{level 2: } \textit{crashes/year} = (\alpha)\ (\textit{total entering AADT})^{\beta 1}\ (\textit{minor road proportion of AADT})^{\beta 2} \tag{8}$$

Two levels of models were required because in a few instances, estimates of annual average daily traffic (AADT) were available only for the intersection as a whole. In most cases, entering AADTs were available for each approach, and level 2 models, which produce better estimates, could be applied. The data set used for the calibration was from a sample of urban intersections in Florida, Maryland, and Toronto, Ontario. These data confirmed the stability of crash reporting over the time period of the conversion data in two states that accounted for 9 of the 24 intersections. The models adopted from previous research were of the same forms as Equations 7-8.

Following recent works by Persaud et al. (1997) and Bonneson and McCoy (1993), the Generalized Linear Interactive Modelling (GLIM) software package (Baker and Nelder 1978) was used for estimating the parameters α (actually $\ln(\alpha)$ since a linear model is fitted) and the βs for Equations 7-8 for all crashes combined and for injury crashes only. GLIM allows the specification of a negative binomial distribution, which now is 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 modelling. In specifying a negative binomial error structure, the parameter k (Equation 5), which relates the mean and variance, had to be iteratively estimated from the model and the data as part of the calibration process.

Typical model calibration results are illustrated in Table 2, which shows the level 2 coefficient estimates for four-legged, one-street stopped intersections. Models were also estimated for three-legged stop controlled intersections. Full details of both the new and existing models are given in the project report (Persaud et al., 1999).

Table 2
Level 2 Reference Population Models for One Street Stopped, Four-Legged Urban Intersections Considering Distribution of AADT Between Major and Minor Road

$\textit{crashes/year} = (\alpha)\ (\textit{total entering AADT})^{\beta 1}\ (\textit{minor road proportion of AADT})^{\beta 2}$

Crash Severity	Jurisdiction	ln(α) (Standard Error)	β1 (Standard Error)	β2 (Standard Error)	*k*
All combined	Maryland	−9.900 (2.04)	1.198 (0.210)	0.370 (0.125)	3.10
	Florida	−9.868 (2.07)			
	Combined	−9.886 (2.01)	1.202 (0.213)	0.376 (0.107)	3.10
Injury	Maryland	−8.271 (2.33)	0.861 (0.249)	0.173 (0.127)	3.34
	Florida	−8.015 (2.37)			
	Combined	−8.613 (2.31)	0.904 (0.245)	0.197 (0.122)	3.24

Because of major operational differences between various roundabout designs and settings, results were analyzed and reported for several groups of conversions for which there were sufficient crash data to provide meaningful results. These include 9 urban single-lane roundabouts that prior to construction were stop controlled, 5 rural single-lane roundabouts that prior to construction were stop controlled, 7 urban multilane roundabouts that prior to construction were stop controlled, and 3 urban intersections converted to roundabouts from traffic signal control.

RESULTS

Table 3 summarizes the estimated crash reductions and provides two measures of safety effects. The first is "index of safety effectiveness" (θ), which is approximately equal to the ratio of the number of crashes occurring after conversion to the number expected had conversion not taken place. The second is the more conventional percent reduction in crashes, which is equal to $100(1-\theta)$. Overall, the empirical Bayes procedure estimated a highly significant 39 percent reduction for all crash severities combined for the 24 converted intersections. Because injury data were not available for the period before construction of the 4 roundabouts in Vail, overall estimates for changes in injury crashes are based on the other 20 intersections. The empirical Bayes procedure estimated a highly significant 76 percent reduction for injury crashes for these 20 converted intersections.

Table 3 also summarizes estimated crash reductions for selected groups of conversions. For the group of 9 urban single-lane roundabouts converted from stop control, the empirical Bayes procedure estimated a highly significant 61 percent reduction for all crash severities combined and a 77 percent reduction for injury crashes. For the group of 5 rural single-lane roundabouts converted from stop control, similar effects were estimated — a 58 percent reduction for all crash severities combined and an 82 percent for injury crashes. For the group of 7 urban multilane roundabouts, however, the estimated effect on all crash severities combined was smaller — a 15 percent reduction. Because injury data were not available for the period before construction of 4 of these roundabouts, overall estimates for changes in injury crashes were not computed for this group of intersections. For the 3 roundabouts converted from traffic signal control, estimated reductions were 32 percent for all crash severities combined and 68 percent for injury crashes. Two of these roundabouts had multilane circulation designs.

For completeness, partial results also are given for individual conversions in a group. Readers are cautioned about drawing conclusions from these results because there is a significant likelihood that the change in safety for individual conversions is due to chance. In some cases, however, there may be logical explanations for an apparent deterioration in safety following roundabout conversion. At the Gainesville site, for example, transportation officials were unable to secure adequate right of way to construct a roundabout to design specifications that would accomplish the desired deflection and speed reduction. This may explain the apparent absence of crash reduction at this site.

Table 3
Estimates of Safety Effect for Groups of Conversions

Group Characteristic Before Conversion/Jurisdiction	Count of Crashes During Period After Conversion		Crashes Expected During After Period Without Conversion (Standard Deviation)		Index of Effectiveness (Standard Deviation)		Percent Reduction in Crashes	
	All	Injury	All	Injury	All	Injury	All	Injury
Single Lane, Urban, Stop Controlled								
Bradenton Beach, FL	1	0	9.9 (3.6)	0 (0)				
Fort Walton Beach, FL	4	0	16.9 (3.9)	2.7 (1.1)				
Gorham, ME	4	0	6.8 (1.4)	0.9 (0.4)				
Hilton Head, SC	9	0	42.8 (6.0)	8.2 (1.9)				
Manchester, VT	1	1	1.7 (0.7)	0 (0)				
Manhattan, KS	0	0	4.2 (1.2)	1.2 (0.5)				
Montpelier, VT	1	1	4.3 (1.8)	1.1 (0.6)				
Santa Barbara, CA	17	2	17.97 (4.9)	0 (0)				
West Boca Raton, FL	7	0	8.1 (3.0)	2.6 (1.3)				
Entire group (9)	44	4	112.6 (10.2)	16.6 (2.6)	0.39 (0.07)	0.23 (0.12)	61	77
Single Lane, Rural, Stop Controlled								
Anne Arundel County, MD	14	2	24.6 (4.0)	6.2 (1.7)				
Carroll County, MD	4	1	15.2 (2.6)	3.2 (0.9)				
Cecil County, MD	10	1	14.3 (2.9)	5.6 (1.4)				
Howard County, MD	14	1	36.7 (5.5)	7.7 (2.1)				
Washington County, MD	2	0	14.4 (3.1)	4.2 (1.3)				
Entire group (5)	44	5	105.2 (8.4)	26.9 (3.4)	0.42 (0.07)	0.18 (0.09)	58	82
Multilane, Urban, Stop Controlled								
Avon, CO	3	0	19.9 (4.9)	0 (0)				
Avon, CO	17	1	12.2 (3.1)	0 (0)				
Avon, CO	13	0	30.1 (5.7)	2.3 (1.0)				
Vail, CO	14	—	19.1 (4.4)	—				
Vail, CO	61	—	50.9 (7.6)	—				
Vail, CO	8	—	9.8 (2.1)	—				
Vail, CO	15	—	11.8 (2.3)	—				
Entire group (7)	131		153.8 (12.4)	n/a	0.85 (0.10)	n/a	15	n/a
Urban, Signalized								
Avon, CO	44	1	49.8 (7.0)	5.4 (1.7)				
Avon, CO	18	0	52.1 (7.0)	5.3 (1.7)				
Gainesville, FL	11	3	4.8 (1.5)	1.3 (0.5)				
Entire group (3)	73	4	106.7 (10.0)	12.0 (2.5)	0.68 (0.10)	0.32 (0.17)	32	68
All conversions	292	14	478.2 (20.7)	57.8 (5.1)	0.61 (0.04)	0.24 (0.07)	39	76

— Data not available

Effects on fatal crashes and those causing incapacitating injuries are more difficult to measure due to the small samples, but indications are that such crashes were substantially reduced. For the 20 converted intersections with injury data, there were 3 fatal crashes during the before period and none during the after period. The fatal crashes may have contributed to the fact that the roundabouts were constructed and may therefore contribute to the regression-to-the-mean phenomenon. There were 27 incapacitating injury crashes during the before period and only 3 during the after period. Taking into account the durations of the before and after periods and increases in traffic volume, and adjusting for regression to the mean (estimated to be roughly 22 percent), the observed value of 3 incapacitating or fatal injury crashes during the after period is substantially and significantly less than the 26.6 expected. The estimated reduction in fatal and incapacitating injury crashes is 89 percent (p<0.001).

There were 3 reported pedestrian crashes during the before period and 1 (with minimal injuries) during the after period. Four bicyclists were injured during the before period and 3 during the after period. However, these samples are too small to be meaningful.

DISCUSSION

Results of this study indicate that converting conventional intersections from stop sign or traffic signal control to modern roundabouts can produce substantial reductions in motor vehicle crashes. Of particular note are the large reductions found in the number of injury crashes, especially those involving incapacitating and fatal injuries. These findings generally are consistent with results of numerous international studies. The accumulated knowledge suggests that roundabout construction should be strongly promoted as an effective safety treatment for intersections. Given the large numbers of injury (700,000) and property damage (1.3 million) crashes that occur each year at traffic signals and stop signs in the United States (National Highway Traffic Safety Administration, 1999), widespread construction of roundabouts can produce substantial reductions in crash losses associated with motor vehicle use on public roads.

It is possible that the smaller safety effect observed for the group of urban intersections that previously were multilane and stop controlled may be due to differences in safety performance of single- versus multilane roundabout designs. However, a firm conclusion cannot be made because of other important differences between conversions in Colorado and those in other states. For example, 3 of the 4 roundabouts in Colorado are part of freeway interchanges that also include nearby intersections that were previously four-way stop controlled. The multilane roundabouts do seem to be effective in eliminating most incapacitating injury crashes.

Crash reductions resulting from conversion of conventional intersections to modern roundabouts can be attributed primarily to two factors: reduced traffic speeds and elimination of specific types of motor vehicle conflicts that frequently occur at angular intersections. These conflicts include left turns against opposing/oncoming traffic, front-to-rear conflicts (often involving the lead vehicle stopping or preparing to stop for a traffic signal or stop sign), and right-angle conflicts at traffic signals and stop signs. Retting et al. (2000) reported that crashes associated with these three intersection traffic conflicts account for two-thirds of police-reported crashes on urban arterials. Red light running crashes, which involve side impacts at relatively high speeds, are especially injury producing (Retting et al., 1995) and can be eliminated through roundabouts conversion.

Although the sample was too small to estimate effects on pedestrian crashes, Scandinavian evaluations of roundabouts conclude that single-lane roundabouts are very safe for pedestrians (Ulf and Jörgen, 1999). Data from this study give no reason to doubt that those experiences can be translated to North America. And none of the multilane roundabouts have had a single pedestrian crash so far, even though there were two crashes during the before period at these sites. Likewise, Scandinavian experience shows that single-lane roundabouts with one-lane entries are very safe for bicyclists.

Some have expressed concern that older drivers may have difficulties adjusting to roundabouts. However, in this study, the average age of crash-involved drivers did not increase following the installation of roundabouts, suggesting that roundabouts do not pose a problem for older drivers.

In addition to reducing the risk of motor vehicle crashes and injuries, conversion to roundabouts can produce other important societal benefits including reductions in vehicle emissions, noise, fuel consumption, and traffic delays (Hyden and Varhelyi, 1999; Jacquemart, 1998). Roundabouts also can improve the aesthetic appearance of intersections by providing opportunities for landscaping and architectural treatments. Roundabouts in place of traffic signals can provide cost savings for local governments by avoiding the expense of new traffic signal construction and maintenance.

Roundabouts are not feasible, nor appropriate, at all intersections. Sufficient right of way must be available for construction of the circular intersection. Typically, a modern roundabout has an outer diameter of approximately 100 feet (30 m). This allows for large enough deflections to reduce speeds to an appropriate level. However, land can be saved compared with signalization because approach roads can be kept narrower. Capacity constraints and limited rights of way eliminate from consideration many busy urban intersections, especially those located in central business districts. Also, intersections with high volumes of both bicycle and motor vehicle traffic may not be good candidates for roundabouts. There remains a need to develop a procedure for estimating the likely safety consequences of a contemplated installation. In the meantime, it is suggested that future installations be patterned after the ones found in this study to have had a very positive safety experience.

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APPENDIX
Empirical Bayes Estimation

The theory is covered in detail elsewhere (Hauer, 1997), so what is presented here is merely an illustration. Consider the Anne Arundel County, Maryland, intersection converted in 1994 for which the crash counts and AADTs on the approaches were as follows.

	Before Conversion	After Conversion
Months (years) of crash data	56 (4.67)	38 (3.17)
Count of total crashes	34	14
Major approaches AADT	10,654	11,956
Minor approaches AADT	4,691	5,264

Estimating B: The Crashes That Would Have Occurred in the After Period without the Conversion

First, using the model from Bonneson and McCoy (1993), the regression estimate (Y) of the number of *total* crashes/year during the before period is:

$$\begin{aligned} P\ (crashes/year) &= 0.000379 \times (major\ road\ AADT)^{0.256} \times (minor\ road\ AADT)^{0.831} \\ &= 0.000379 \times (10{,}654)^{0.256} \times (4{,}691)^{0.831} = 4.58. \end{aligned}$$

Then, the expected annual number of crashes during the before period is estimated as:

$$m_b = (k + x_b) / (k/P + y_b),$$

where x_b is the count of crashes during the before period of length y_b years and $k = 4.0$ is a parameter estimated in the regression model. Thus, the expected annual number of crashes during the before period is:

$$m_b = (4.0 + 34) / [(4/4.58) + 4.67] = 6.860.$$

To estimate *B*, the length of the after period and differences in the AADTs between the before and after period must be considered. This is accomplished by first multiplying the expected annual number of crashes in the before period by *R*, the ratio of the annual regression predictions for the after and before periods. In the after period:

$$crashes/year = 0.000379 \times (11{,}956)^{0.256} \times (5{,}264)^{0.831} = 5.19.$$

The ratio *R* of the after period to the before period regression predictions is:

$$R = 5.19/4.58 = 1.133,$$

which gives:

$$m_a = R \times m_b = 1.133 \times 6.860 = 7.772 \text{ crashes/year.}$$

Finally, to the estimate of *B*, the number of crashes that would have occurred in the after period had the conversion not taken place, m_a is multiplied by y_a, the length of the after period in years. Thus:

$$B = 7.772 \times 3.17 = 24.61.$$

Recall that 14 crashes actually occurred. The variance of *B* is given by:

$$Var(B) = B \times R \times y_a/(p + y_b) = 24.61 \times 1.133 \times 3.17 / (0.873 + 4.333) = 16.93$$

Estimation of Safety Effect

In the estimation of changes in crashes, the estimate of *B* is summed over all intersections in the converted group and compared with the count of crashes during the after period in that group (Hauer 1997). For the 5 conversions in Maryland, the table below gives the estimates of *B*, variance of these estimates, and the count of crashes in the after period.

After Period Count (*A*)	Empirical Bayes Estimate (*B*)	*Var*(*B*)
14	36.71	30.63
14	24.62	15.95
2	14.38	9.40
10	14.33	8.55
4	15.16	6.76
Sum = λ = 44	Sum = π =105.19	Sum = 71.29

The variance of *B* is summed over all conversions. The variance of the after period counts, *A*, assuming that these are Poisson distributed, is equal to the sum of the counts. There are two ways to estimate safety effect as shown below. For each, the estimation of the variance is illustrated.

Method 1: Reduction in Expected Number of Crashes (δ)

This is the difference between the sums of the *B*s and *A*s over all sites in a conversion group. Let:

$$\pi = \Sigma B$$
$$\lambda = \Sigma A;$$

thus:

$$\delta = \pi - \lambda.$$

For the Maryland conversion data in the table above:

$$\delta = 105.19 - 44 = 61.19.$$

The variance of δ is given by:

$$Var(\delta) = \Sigma\ Var(B) + \Sigma\ Var(A).$$

For the Maryland conversion data in the table above:

$$Var(\delta) = 71.29 + 44 = 115.29.$$

Method 2: Index of Effectiveness (θ)

A biased estimate of θ is given by:

$$\theta = \lambda / \pi.$$

The percent change in crashes is in fact 100(1–θ); thus a value of $\theta = 0.7$ indicates a 30 percent reduction in crashes. From Hauer (1997), an approximate unbiased estimate of θ is given by:

$$\theta = (\lambda/\pi) / \{1 + [Var(\pi)/\pi^2]\}.$$

For the Maryland conversion data in the table above:

$$\theta = (44/105.19)/[1 + (71.29/105.19^2)] = 0.416.$$

The variance of θ is given by:

$$Var(\theta) = \theta^2\{[Var(\lambda) / \lambda^2] + [Var(\pi)/\pi^2]\} / [1+Var(\pi)/\pi^2]^2.$$

For the Maryland conversion data in the table above:

$$Var(\theta) = 0.416^2\ [(44/44^2) + (71.29/105.19^2)] / [1 + (71.29/105.19^2)]^2 = 0.0050.$$