

Observational Before-After Study of the Safety Effect of U.S. Roundabout Conversions Using the Empirical Bayes Method

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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. This interest has created a need for data regarding the safety effect of roundabouts. This paper evaluates changes in motor vehicle crashes following conversion of 23 intersections from stop sign and traffic signal control to modern roundabouts. The settings, located in 7 states, were a mix of urban, suburban, and rural environments with both single-lane and multilane designs in the urban sample and the rural sample consisting of only single-lane designs. A before-after study was conducted using the empirical Bayes procedure, which accounts for regression-to-the-mean and the traffic volume changes that usually accompany conversion of intersections to roundabouts. Overall, for the 23 intersections combined, this procedure estimated highly significant reductions of 40 percent for all crash severities combined and 80 percent for all injury crashes. Reductions in the numbers of fatal and incapacitating injury crashes were estimated to be about 90 percent. In general, the results are consistent with numerous international studies and suggest that roundabout installation should be strongly promoted as an effective safety treatment for intersections. Since the empirical Bayes approach is relatively new in safety analysis, a secondary objective of the paper is to demonstrate the potential of this methodology in the evaluation of safety measures.

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 (1).

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 40 km/h (25 mph) or more. Drivers typically enter older traffic circles at speeds of 55 km/h (35 mph) or more. In contrast, modern roundabouts are designed for lower entry speeds, 25-40 km/h (15-25 mph) for urban roundabouts and 40-50 km/h (25-30 mph) for rural designs (2). 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.

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 (3) 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; with the more severe injury crashes (resulting in hospital admissions) being reduced by 81 percent.

Troutbeck (4) 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 when sites with an unusually high counts of crashes are selected for treatment. A thorough review of the literature was conducted by Elvik et al. (5), 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 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. In addition, the extent of the effects of the regression-to-the-mean bias was not known.

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 (6) 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 (7) 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, given the relatively small sample size.

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. These tools not only control for regression-to-the-mean, but also reduce uncertainty in the results and properly account for the effects of traffic volume changes that inevitably accompany the conversion of conventional intersections to roundabouts.

METHOD

The empirical Bayes before-after procedure (8) 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:

$$B-A, \quad (1)$$

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.

B was, in general, estimated using the empirical Bayes procedure in which 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 model 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:

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

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

$$w_1 = P/(k + nP) \quad (3)$$

$$w_2 = k/(k + nP), \quad (4)$$

where

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

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:

$$\text{Var}(A) = A. \quad (6)$$

Uncertainty in the estimates of safety effects also can be described with the use of likelihood functions, the theory behind which has been presented in the full project report (9).

ASSEMBLY OF DATA AND REGRESSION MODELS

Data for Converted Intersections

The analyses were confined to 7 states — Colorado, Florida, Kansas, Maine, Maryland, South Carolina, and Vermont — where a total of 23 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 23 intersections studied, 19 were previously controlled by stop signs, and 4 were controlled by traffic signals. Fourteen 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. The identification of crashes associated with the intersection was up to the individual jurisdictions providing the data. It was expected that there would be slight variations in how intersection crashes are defined, but this inconsistency was not expected to materially affect the results. 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

Jurisdiction	Year Opened	Control Before ^a	Single or Multilane	AADT		Months		Crash Count			
				Before	After	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	6	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
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

^a1 = four-legged, one street stopped; 2 = three-legged, one street stopped; 4 = other unsignalized; 6 = signal

Regression Models

From data about intersections not converted and a consideration of existing models, regression models required for the empirical Bayes estimates of safety effect (Equations 2-5) were assembled. These models were of the form:

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

$$\text{level 2: } \text{crashes/year} = (\alpha) (\text{total entering AADT})^{\beta_1} (\text{minor road proportion of AADT})^{\beta_2} \tag{8}$$

Two levels of models were required because for a few conversions, 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.

New models were calibrated for stop controlled urban intersections, whereas other models, similar in form to Equations 7-8, were adopted from Lord (10) for signalized intersections and Bonneson and McCoy (11) for rural stop controlled intersections. For urban stop controlled intersections, two levels of models were calibrated:

The data set used for the calibration of new models for urban stop controlled intersections consisted of crash counts and approach AADTs for a sample of urban and suburban intersections in Toronto, Maryland, and Florida. The Maryland data consisted of 10 years of crash counts from 1989 to 1998, while Florida had 6 years of crash counts from 1993 to 1998, and Toronto had 6 years of crash counts covering the period from 1990 to 1995. Examination of Table 1 indicates that the period of the reference data provides a good representation of that in the conversion data set. These data also confirmed the stability of crash reporting over the time period of the conversion data in two states that accounted for 9 of the 23 intersections.

There were 86 four-legged intersections — 18 from Maryland, 9 from Florida, and 59 from Toronto. Exploratory analysis indicated that the data sets from the 3 jurisdictions could be combined even if separate model coefficients had to be estimated for each of the jurisdictions. Although none of the conversions are in Toronto, it was decided to include this data set to increase the reliability of the model estimates after it was found that the model coefficients for Toronto and Maryland were quite similar for four-legged intersections. This finding rationalized the use of a data set for three-legged intersections that was almost exclusively made up of Toronto intersections. Very few of the Maryland and Florida intersections in the NCHRP data set were of this category. Details of the data are summarized in Table 2.

TABLE 2 Details of the Data Set Used to Calibrate Regression Models

Intersection Class	Jurisdiction	Number of Intersections	Years of Data	Range of Minor Road AADT	Range of Major Road AADT	Total Crashes	Injury Crashes
Four-legged	Maryland	18	10	365–3,133	8,625–52,144	597	177
	Florida	9	6	1,064–3,487	15,017–39,558	228	79
	Toronto	59	6	384–8,487	5,755–52,598	1,317	357
	All	86		365–8,487	5,755–52,598	2,142	613
Three-legged	Maryland	3	10	858–1,992	21,294–40,535	177	64
	Florida	3	6	722–2,006	16,012–25,905	64	27
	Toronto	117	6	105–7,771	9,101–51,725	1,690	472
	All	123		105–7,771	9,101–51,725	1,931	563

Following recent works by Persaud et al. (12) and Bonneson and McCoy (11), the Generalized Linear Interactive Modelling (GLIM) software package (13) was used for estimating the parameters α (actually $\ln(\alpha)$ since a linear model is fitted) and the β s 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. Model calibration results are illustrated in Tables 3-5.

It was assumed that the models could be transferred across jurisdictions. Injury models calibrated for Florida and Maryland stop controlled intersections indicated that this assumption was reasonable for injury crashes. For crashes of all severities combined, differences in reporting practice across jurisdictions created a difficulty with this assumption. In the end, we decided to use the models as originally calibrated for all severities combined since it was determined that, overall, this would provide a conservative estimate of safety effect. The resulting estimation errors are likely to be small since the counts of crashes of all severities combined is generally large, meaning that relatively little weight is given to the model predictions in the empirical Bayes estimation.

TABLE 3 Level 2 Reference Population Models for One Street Stopped, Four-Legged Urban Intersections Considering Distribution of AADT Between Major and Minor Road, $\text{crashes/year} = (\alpha) (\text{total entering AADT})^{\beta_1} (\text{minor road proportion of AADT})^{\beta_2}$

Crash Severity	Jurisdiction	$\ln(\alpha)$ (standard error)	β_1 (standard error)	β_2 (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)	
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)	

TABLE 4 Level 1 Reference Population Models for One Street Stopped Four-Legged Intersections Based on Total Entering AADT, $crashes/year = (\alpha) (total\ entering\ AADT)^\beta$

Crash Severity	Jurisdiction	$\ln(\alpha)$ (standard error)	α (standard error)	k
All combined	Maryland	-7.062 (1.89)	} 0.804 (0.184)	2.71
	Florida	-6.803 (1.90)		
	Combined	-6.834 (1.87)	0.796 (0.183)	2.67
Injury	Maryland	-6.904 (2.07)	} 0.673 (0.201)	3.19
	Florida	-6.556 (2.08)		
	Combined	-7.058 (2.06)	0.695 (0.201)	3.05

TABLE 5 Reference Population Models for One Street Stopped Three-Legged Intersections

Level 1: $crashes/year = (\alpha) (total\ entering\ AADT)^\beta$

Level 2: $crashes/year = (\alpha) (total\ entering\ AADT)^{\beta1} (minor\ road\ proportion\ of\ AADT)^{\beta2}$

Severity	Model Level	$\ln(\alpha)$ (standard error)	β (standard error)	$\beta1$ (standard error)	$\beta2$ (standard error)	k
All combined	Level 1	-4.382 (1.89)	0.516 (0.184)	1.053 (0.163)	0.559 (0.066)	2.51
	Level 2	-8.051 (1.60)				4.31
Injury	Level 1	-8.640 (2.26)	0.809 (0.219)	1.225 (0.270)	0.466 (0.0937)	2.61
	Level 2	-11.364 (2.16)				3.76

ANALYSIS — EMPIRICAL BAYES ESTIMATION

The theory is covered in detail elsewhere (8), so what is presented here is merely an illustration. Consider the Anne Arundel County, Maryland, intersection (Table 1) converted in 1994 for which the crash counts and AADTs on the approaches are shown in Table 6.

TABLE 6 Data for Example Conversion

	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 (11), the regression estimate (Y) of the number of total crashes/year during the before period is:

$$P (crashes/year) = 0.000379 \times (major\ road\ AADT)^{0.256} \times (minor\ road\ AADT)^{0.831} \tag{9}$$

$$= 0.000379 \times (10,654)^{0.256} \times (4,691)^{0.831} = 4.58.$$

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

$$m_b = (k + x_b) / (k/P + y_b), \tag{10}$$

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:

$$B = 7.772 \times 3.17 = 24.63.$$

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

$$\begin{aligned} \text{Var}(B) &= (m_b) \times (R \times y_a)^2 / [(k/P) + y_b] \\ &= 6.860 \times (1.133 \times 3.17)^2 / (0.873 + 4.67) = 15.96 \end{aligned} \tag{12}$$

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 (8). For the 5 conversions in Maryland, Table 7 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	24.63	15.96
2	14.38	9.40
10	14.33	8.55
4	15.16	6.76
Sum = $\lambda = 44$	Sum = $\pi = 105.21$	Sum = 71.30

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:

$$\begin{aligned} \pi &= \sum B \\ \lambda &= \sum A; \end{aligned}$$

thus:

$$\delta = \pi - \lambda. \tag{13}$$

For the Maryland conversion data in the table above:

$$\delta = 105.21 - 44 = 61.21.$$

The variance of δ is given by:

$$\text{Var}(\delta) = \sum \text{Var}(B) + \sum \text{Var}(A). \tag{14}$$

For the Maryland conversion data in the table above:

$$\text{Var}(\delta) = 71.30 + 44 = 115.30.$$

Method 2: Index of Effectiveness (θ)

A biased estimate of θ is given by:

$$\theta = \lambda / \pi. \quad (15)$$

The percent change in crashes is in fact $100(1-\theta)$; 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:

$$\theta = (\lambda/\pi) / \{1 + [\text{Var}(\pi)/\pi^2]\}. \quad (16)$$

For the Maryland conversion data in the table above:

$$\theta = (44/105.21) / [1 + (71.30/105.21^2)] = 0.421.$$

The variance of θ is given by:

$$\text{Var}(\theta) = \theta^2 \{ [\text{Var}(\lambda)/\lambda^2] + [\text{Var}(\pi)/\pi^2] \} / [1 + \text{Var}(\pi)/\pi^2]^2. \quad (17)$$

For the Maryland conversion data in the table above:

$$\text{Var}(\theta) = 0.421^2 [(44/44^2) + (71.30/105.21^2)] / [1 + (71.30/105.21^2)]^2 = 0.0050.$$

RESULTS

Table 8 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 40 percent reduction for all crash severities combined for the 23 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 80 percent reduction for injury crashes for these 20 converted intersections. These estimates are slightly lower than those that were obtained using a simple before and after comparison instead of the empirical Bayes procedure.

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 8 urban single-lane roundabouts that prior to construction were stop controlled, 5 rural single-lane roundabouts that prior to construction were stop controlled, 6 urban multilane roundabouts that prior to construction were stop controlled, and 4 urban intersections converted to roundabouts from traffic signal control. For the group of 8 urban single-lane roundabouts converted from stop control, the empirical Bayes procedure estimated highly significant reductions of 72 percent for all crash severities combined and 88 percent 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 6 urban multilane roundabouts, however, the estimated effect on all crash severities combined was smaller — a 5 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 4 roundabouts converted from traffic signal control, estimated reductions were 35 percent for all crash severities combined and 74 percent for injury crashes. Three 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. 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

TABLE 8 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)				
West Boca Raton, FL	7	0	8.1 (3.0)	2.6 (1.3)				
Entire group (8)	27	2	94.6 (9.0)	16.6 (2.6)	0.28 (0.06)	0.12 (0.08)	72	88
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)				
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 (6)	118		123.7 (11.0)	n/a	0.95 (0.10)	n/a	5	n/a
Urban, Signalized								
Avon, CO	44	1	49.8 (7.0)	5.4 (1.7)				
Avon, CO	13	0	30.1 (5.7)	2.3 (1.0)				
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 (4)	86	4	131.7 (10.9)	15.0 (2.7)	0.65 (0.09)	0.26 (0.14)	35	74
All conversions (23)	275	12	454.6 (19.8)	58.5 (5.1)	0.60 (0.04)	0.20 (0.06)	40	80

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 4 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 give conclusive evidence on the safety of these road-user groups at roundabouts.

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. The use of the state-of-the-art empirical Bayes methodology to account for regression to the mean and traffic volume changes reinforces the validity of these findings when taken with the fact that they are generally consistent with the 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 (14), widespread construction of roundabouts can produce substantial reductions in injuries and property damage 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 and which were all in Colorado 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, the 2 Avon, Colorado roundabouts that previously were multilane and stop controlled 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 or reduction 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. (15) reported that crashes associated with these 3 types of 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 (16); such impacts are virtually non-existent at roundabouts.

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 (17). 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 (18,19). 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, useful information may be obtained from the Federal Highway Administration Roundabout Guide (2).

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