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Safety and Economic Assessment of Converting Two-Way Stop-Controlled Intersections to Roundabouts on High Speed Rural Highways

by Shanshan Zhao, Aemal J. Khattak and Eric C. Thompson

This research addressed two questions: "Are roundabouts on rural high-speed roadways safer than two-way stop controlled (TWSC) intersections?" and "What economic benefits can be expected from converting TWSC intersections to roundabouts in terms of safety improvement?" Crash and traffic data on four TWSC intersections that were converted to roundabouts in Kansas were analyzed using the empirical Bayes before-after evaluation method and crash costs were applied to evaluate economic benefits. Analysis showed that fatal, non-fatal, and property-damage-only crashes were reduced by 100%, 76.47%, and 35.49%, respectively. The annual monetary value from this reduction was between $1.0—$1.6 million in 2014 dollars.

INTRODUCTION

Construction of modern roundabouts is becoming common in the United States. Their use in the United States began in 1990s and they have been increasingly popular since then (Rodegerdts 2007). Construction of roundabouts is one way to reduce vehicle collisions and improve the efficiency of intersections (Nebraska Department of Roads 2012). Numerous studies in the United States have shown that roundabouts are effective in urban environments but published literature is relatively sparse on the safety performance of roundabouts constructed on high-speed (45-65 mph) roads in rural and suburban areas.

A concern with roundabouts constructed on high-speed rural roadways is the speed differential of vehicles traveling on the roundabout approaches and roundabout entries. Roundabouts on high-speed roadways are not "high-speed roundabouts" (Isebrands and Hallmark 2012). With a well-designed roundabout, drivers are allowed to navigate at a reduced speed (15 to 30 mph) inside the roundabout (Isebrands and Hallmark 2012, Persaud et al. 2001, Rodegerdts 2010). Inadequate signing, absence of nighttime lighting, and possible lower levels of drivers' alertness in rural environments may be some of the reasons causing high approach speeds and driver confusion at the roundabouts (Thomas and Nicholson 2003, Appleton and Clark 1998). The research questions addressed in this research therefore were: "Are roundabouts on rural high-speed roadways safer than traditional two-way stop controlled (TWSC) intersections?" and "What economic benefits can be expected for the conversion from TWSC intersections to roundabouts in terms of safety improvement?" Therefore, the objectives were to statistically quantify the changes in reported crashes before and after conversion of rural TWSC intersections with high-speed approaches to roundabouts and quantitatively evaluate the economic values of these changes.

To answer the above questions, crash records on several TWSC intersections that were subsequently converted to roundabouts were collected from Kansas Department of Transportation (KDOT). A before-after analysis using the Empirical Bayes (EB) method as given in the *Highway Safety Manual* (AASHTO 2010a) was utilized. An economic evaluation was conducted based on the results of this safety analysis. The organization of the remaining paper includes a review of pertinent literature followed by the modeling background. The next section presents results of the EB before-after crash analysis while the ensuing section shows results of the economic evaluation based on avoided crashes and reduced severities. The last section provides conclusions and a discussion.

LITERATURE REVIEW

Safety Studies on Rural Roundabouts with High-Speed Approaches

Several studies have shown that roundabouts reduce crash frequencies as well as severities compared with their traditional traffic control counterparts (Rodegerdts 2007, Persaud et al. 2001, Rodegerdts 2010, Flannery and Datta 1996, Lanani 1975, Cunningham 2007, Maycock and Hall 1984, Persaud et al. 2000, Tudge 1990). Most of the roundabouts studied were in urban settings. Studies specially pertaining to rural roundabouts with high-speed approaches were relatively sparse; however, the following studies were found on rural roundabouts with high-speed approaches in the U.S. during the literature search.

Myers (1999) studied crashes at five rural roundabouts with high-speed approaches in Maryland by analyzing data gathered three years before and three years after the installation of the roundabouts. A before-after analysis showed that the average crash rates at these five intersections were reduced by 59% and the injury or serious crashes were reduced by 80%. Persaud et al. (2001) conducted an EB observational before-after study on crashes when 23 intersections were converted from stop sign and traffic signal control to modern roundabouts. Results indicated a 40% reduction in all crashes and an 80% reduction in injury crashes. Of all the intersections, the five rural single-lane roundabouts experienced a 58% reduction in total crashes and an 82% reduction in injury crashes, which were both higher than the average of all settings. Ritchie and Lenters (2005) compared the performance of roundabouts and traffic signals with high-speed approaches (45+ mph). They reported roundabouts out-performing their signalized counterparts by nearly a 50% reduction in injury and fatal crashes; one specific site demonstrated an 80% reduction in expected crashes after conversion to roundabouts.

Rodegerdts (2007) conducted an EB before-after study comparing the performance of traditionally controlled intersections with roundabouts. The study concluded that roundabouts reduced both overall crash rates and injury crash rates in a wide range of settings including urban, suburban, and rural. All types of crashes were reduced by approximately 35.4% and injury crashes were reduced by 75.8%. For the nine rural roundabouts studied in the report, which were all converted from TWSC intersections, the total crash reduction was 71.5%, and injury crashes were reduced by 87.3%. For the 24 suburban roundabouts converted from signalized or TWSC intersections, the total crash reduction and injury crash reduction were about 42% and 68%, respectively.

In Maryland, crash reports of 149 crashes at 29 single-lane roundabouts and 134 crashes at nine double-lane roundabouts were reviewed (Mandavilli et al. 2009). Several of the roundabouts in the study were rural roundabouts on high-speed roadways; about three-quarters of all reported collisions were at the roundabout entrance, and high approach speed was an important factor in crashes.

Isebrands and Hallmark (2012) conducted a study on rural roundabouts with high-speed approaches. A before-after crash analysis using a negative binomial regression model and a before-after EB estimation were both conducted showing consistent results. The negative binomial regression showed that total crashes were reduced by 63% and injury crashes by 88% at 19 rural roundabouts with high speed approaches. The before-after EB estimation showed reductions of 67% in total crashes and 87% in injury crashes.

An evaluation of 24 roundabouts was conducted in Wisconsin (Qin et al. 2013). The EB before-after analysis showed an overall reduction of 9.2% in total crashes in all locations and a 52% reduction in fatal and injury crashes. Eight of the 24 roundabouts were identified as rural; these roundabouts experienced reductions of 45% in total crashes and 56% in fatal and injury crashes. The study included 11 roundabouts with a posted speed limit of 45 mph or greater. These roundabouts experienced reductions of 34% in total crashes and 49% in fatal and injury crashes.

A study of conversion to roundabouts in Belgium (Antoine 2005) showed an average of 42% decrease in injury crashes and 48% decrease in serious crashes in all settings. Roundabouts in rural open country environment, which usually have high speed approaches, had a 50% crash reduction. Roundabouts in suburban locations had a crash reduction of 46% and those in urban areas a reduction of 15%.

Economic Benefits of Conversion to Roundabouts

Economic benefits can be expected from conversions of intersections to roundabouts. The main safety benefits of converting a TWSC intersection to a roundabout are the assumed savings to the public due to a reduction in crashes in the before-after periods within the project area. Non-safety related benefits may include reductions in motorist delays, fuel consumption, and vehicle emissions. Safety benefit estimation requires a crash history before and after conversion to a roundabout. The EB before-after analysis can be used to eliminate the effects of regression-to-the-mean and changes in traffic volumes during the before-after periods. Safety benefits are then estimated by multiplying the change in number of crashes of each severity level by the average costs of each crash (Rodegerdts 2010).

As reviewed earlier, roundabouts reduce crashes compared with stop-controlled or signalized intersections. Table 1 presents an estimate of average economic costs on a per accident basis for each severity level for the year 2000 available from the American Association of State Highway and Transportation Officials (AASHTO 2010b). Estimates for 2014, which were based on values for 2000, and updated from 2000 to 2014 based on the change in the value of a statistical life reported for 2000 (Blincoe et al. 2000) and 2014 (Rogoff and Thomson 2014). There has been a sharp increase in the measured value of a statistical life from $3.4 million in 2000 to $9.4 million in 2014.

Table 1: Average Comprehensive Cost of Motor-Vehicle Crashes by Injury Severity, 2000 and 2014

Severity	Economic Cost Per Accident (2000 Dollars)*	Economic Cost Per Accident (2014 Dollars)
Fatal	$3,753,200	$10,480,100
Non-Fatal Injury	$138,100	$385,600
Property Damage Only	$3,900	$10,900
All Injury	$202,300	$567,700

* Source: AASHTO 2010b

The Office of Management and Budget issued significant upward revisions to its recommended Value of a Statistical Life in both 2008 and 2012 to reflect advancements in the economics literature. The 2008 revision to $5.8 million was made due to: 1) the introduction of the growth in real wages as a factor in updating estimates and 2) the substitution of the consumer price index for the GDP deflator when updating estimates (Szabat and Knapp 2009). The 2012 revision utilized improved estimates for the Value of a Statistical Life based on studies using the newly available Census of Fatal Occupational Injuries produced by the United States Bureau of Labor Statistics. The result was an increase in the recommended Value of Statistical Life from $6.2 million in 2011 to $9.1 million in 2012 (Trottenberg and Rivkin 2013).

The reviewed literature showed that roundabouts are mostly safer than stop-controlled or signalized intersections in terms of total crash frequencies, especially injury crash frequencies. Roundabouts converted from stop-controlled or signalized intersections with high-speed approaches in rural and suburban areas seem to have greater crash reductions than roundabouts in low-speed urban settings (Persaud et al. 2001; Antoine 2005; Rodegerdts 2007). With a significant reduction in crash frequency and severities, substantial safety benefits of the conversion can be expected. However, more research work is still needed before we draw the conclusion that roundabouts are the most appropriate and cost-effective control for intersections with high-speed approaches in rural settings. This study therefore explored the safety performance and its corresponding economic values of roundabouts with high-speed approaches in rural settings using data obtained from Kansas; the studied roundabouts were all TWSC intersections before conversion.

MODELING BACKGROUND

The EB before-after safety evaluation method uses safety performance functions (SPFs) to estimate what the expected average crash frequency would have been at a location where a safety improvement treatment was implemented, had the treatment not been implemented. The expected average crash frequency can be denoted as $N_{expected,After}$ or simply $N_{expected,A}$, which stands for the expected crash frequency for the after period assuming the treatment was not applied and the location remained the same as before. It then compares the actual observed crashes after the treatment application, which is denoted as $N_{observed,After}$ or simply $N_{observed,A}$, to the expected average if the treatment had not been applied, $N_{expected,A}$, to determine the treatment's safety effectiveness (AASHTO 2010a).

The fluctuation of crashes over time at a location makes it difficult to determine whether the crash frequency changes are due to a safety treatment or are due to the natural fluctuation. When a site experiences high (low) crash frequency in a certain period, it is statistically probable that it will experience a comparatively low (high) crash frequency in the following period of similar duration. This phenomenon is known as regression-to-the-mean (RTM). Compared with simple before-after analysis, EB results are adjusted by changes in traffic volumes and corrected for potential biases from the RTM effect. The EB method is used in the *Highway Safety Manual* (AASHTO 2010a); the procedures are described as follows.

The predicted average crash frequency for a year, $N_{predicted}$, is expressed as per intersection per year.

(1) $N_{predicted} = N_{spfx} \times (CMF_{1x} \times CMF_{2x} \times \ldots \times CMF_{yx}) \times C_x$

Where N_{spfx} = predicted average crash frequency determined for base condition of the SPF developed for site type x,

CMF_{yx} = crash modification factors specific to SPF for site type x, and

C_x = calibration factor to adjust SPF for local conditions for site type x.

The expected average crash frequency for the before treatment period is expressed as per intersection summed for the entire before period.

(2) $N_{expected,B} = w_{i,B}N_{predicted,B} + (1- w_{i,B})N_{observed,B}$

Where, the weight for each site i is determined as:

(3) $w_{i,B} = 1 / (1 + k\sum_{Before\ years} N_{predicted})$

$N_{expected,B}$ = expected average crash frequency at site i for the entire before treatment period,

$N_{observed,B}$ = observed crash frequency at site i for the entire before treatment period, and

k = over-dispersion parameter for the applicable SPF.

The predicted average crash frequency for each site i during each year of the after treatment period can be calculated in the same way. The adjustment factor, r_i, which accounts for the difference between the before and after treatment periods in duration and traffic volume at each site i is:

(4) $r_i = (\sum_{After\ years} N_{predicted,A}) / (\sum_{Before\ years} N_{predicted,B})$

The expected average crash frequency for each site i over the entire after period in the absence of the treatment is:

(5) $N_{expected,A} = N_{expected,B} \times r_i$

The estimate of the safety effectiveness of the treatment at site i can be expressed in the form of an odds ratio,

(6) $OR_i = N_{observed,A} / N_{expected,A}$

The percentage crash change at site i is:

(7) $P_i = 100 \times (1 - OR_i)$

The overall effectiveness of the treatment for all sites combined, in the form of an odds ratio, is expressed as:

(8) $OR' = (\sum_{All\ sites} N_{observed,A}) / (\sum_{All\ sites} N_{expected,A})$

The odds ratio above is potentially biased. In statistics, this is called the bias for the ratio estimator. It can be shown with Jensen's inequality as

(9) $E(X/Y) = E[X\,(1/Y)] = E(X)\,E(1/Y) \geq E(X) \times [1/E(Y)] = E(X)/E(Y)$

The inequality is because the equal deviations of y below and above $E(Y)$ exert unequal influence on the ratio $1/y$. For example, suppose that the random variable Y takes on the values of $y = 0.5$ and $y = 1.5$ with equal probability so $E(Y) = 0.5*(0.5+1.5) = 1.0$ while $E(1/Y) = 0.5*(1/0.5+1/1.5) = 1.33$, which is not $1/E(Y) = 1.0$ (Hauer 1997).

An unbiased estimate of the overall effectiveness is:

(10) $OR = OR' / [1 + Var\,(\sum_{All\ sites} N_{expected,A}) / (\sum_{All\ sites} N_{expected,A})^2\,]$

In which, $Var(\sum_{All\ sites} N_{expected,A}) = \sum_{All\ sites} [(r_i)^2 \times N_{expected,B} \times (1 - w_{i,B})]$.

EB BEFORE-AFTER CRASH ANALYSIS

Crash and Traffic Data

Crash data on four rural high-speed (45-65 mph) intersections with two-way stop control that were converted to roundabouts were obtained from the Kansas Department of Transportation (KDOT). The period when two-way stop control was in effect was referred to as the "before" time period (i.e., before conversion to roundabouts) while the roundabout period was termed as the “after” period; conversion to roundabout was the safety treatment in each case. Crashes reported during the conversion year were excluded to remove any construction effects. Information for fatal, injury, and property-damage-only (PDO) crashes for each year in the before and after periods was utilized in the analysis. Table 2 presents the locations of the four roundabouts, the crash counts in the two time periods, and annual average daily traffic (AADT) before and after roundabout conversion. Due to the availability of the crash data, varied lengths of years were applied in the before and after time periods. For example, for the site US-400 & K-47, crash data for five years before the conversion (2004-2008) and data for three years after (2010-2012) were used. Data for 2009 were excluded since 2009 was the construction year. Notice that the application of different lengths of years would not affect the conclusion because the EB method already takes into account the changes of years when calculating the expected crashes for the after period.

The AADT information was collected from a KDOT historical state traffic flow map. In some instances, AADT on the corresponding major road legs were different, in which case the larger of the two values was recorded as the AADT for the major road (AADTmaj), consistent with the guidance in the *Highway Safety Manual* (AASHTO 2010a). The AADT on the minor roads (AADTmin) were determined in a similar manner. Traffic volumes did not change significantly after conversion of the TWSC intersections to roundabouts except for the US-400 & K-47 intersection. For the US-400 & K-47 intersection, AADT on major and minor approaches were decreased by 11% and 25%, respectively. For the other three sites, changes of AADT on major and minor approaches were less than 10%. Traffic volumes for the four sites ranged from 2,000 to 7,000 vehicles/day. Annual average crash rates before conversion were from 4.2 to 5.0 accidents/year.

While the characteristics of these four TWSCs that were converted to roundabouts may not represent all TWSC intersections in the U.S. with respect to traffic volumes and number of crashes, they should be representative of TWSCs that have comparable crash histories and traffic volumes.

EB Before-After Analysis

Table 3 presents the results of the EB before-after analysis for total, fatal, non-fatal injury, and PDO crashes reported at each site. The odds ratios (column 5) were calculated by dividing observed number of crashes by expected number of crashes; a value smaller than 1.00 indicates that a particular location experienced fewer crashes after conversion to roundabouts. Percentage reductions (column 6) represent crash reduction rates; larger values represent greater crash reductions. The intersection at US-400 & K-47 experienced an increase in total crashes after conversion (from an expected total of 8.03 to an actual observed total of nine crashes within three years), a 100% decrease in fatal crashes (from an expected value of 0.17 to an actual observed of zero fatal crashes), and a slight decrease in injury crashes (from an expected value of 4.26 to an actual observed of four non-fatal injury crashes). The other three locations had a significant percentage reduction ranging from 45% to 84% for total crashes, 100% for fatal crashes, and from 80% to 100% for injury crashes. The results for the PDO crashes, however, were mixed as two locations (US-400 & K-47, from 3.6 to 5.0; US-50 & US-77, from 6.3 to 7.0) experienced an increase in such crashes.

Table 4 presents the results of aggregated analysis of all four locations, i.e., crashes at all locations in each time period were pooled for the analysis. The overall effectiveness of the treatment (conversion to roundabouts) for all sites combined can be expressed in the form of an odds ratio (column 5). This odds ratio is potentially biased, but an unbiased estimate of the overall effectiveness is presented in column 6. Overall, all types of crashes were reduced after conversion to roundabouts. Total crashes were reduced by 58.13%; fatal crashes were reduced by 100%; injury crashes were reduced by 76.47%; while PDO crashes were reduced by 35.49%. The results are mostly consistent with studies reported in the literature.

Table 2: Information on the Four Intersections/Roundabouts*

Intersecting Roads	Conversion Year	Number of Legs	Before Period					After Period					Posted Speed
			Years	Total Crashes	Fatal and Injury Crashes	AADTmaj/ truck %	AADTmin/ truck %	Years	Total Crashes	Fatal and Injury Crashes	AADTmaj / truck %	AADTmin/ truck %	Major/Mi-nor (mph)
US-400 & K-47	2009	4	2004-2008	21	13	4116 /22%	3004 /10%	2010-2012	9	4	3673 /24%	2250 /13%	65/65
US-400/US-69A & K-66	2008	4	2003-2006	19	10	6818 /9%	4940 /6%	2009-2012	3	0	6730 /9%	4923 /7%	65/45
E. Jct. of US-77 & US-166	2009	4	2004-2008	21	11	5036 /13%	4192 /15%	2010-2012	3	1	5493 /12%	4157 /12%	65/55
US-50 & US-77	2006	5	2001-2004	20	14	3545 /48%	2190 /11%	2007-2010	9	2	3370 /49%	2028/ 16%	55/45

* Source: Kansas Department of Transportation (KDOT)

Table 3: Empirical Bayes Analysis of All Crashes

Intersecting Roads	Observed Total Crashes (Before)	Observed Total Crashes (After)	Expected Total Crashes (After)	Odds Ratio (Observed/Ex-pected, After)	Percentage Reduction % [100*(1-Odds Ratio)]
Total Crashes					
US-400 & K-47	21.00	9.00	8.03	1.12	-12.10
US-400/US-69A & K-66	19.00	3.00	19.34	0.16	84.48
E. Jct. of US-77 & US-166	21.00	3.00	13.64	0.22	78.01
US-50 & US-77	20.00	9.00	16.31	0.55	44.81
Fatal Crashes					
US-400 & K-47	3.00	0.00	0.17	0.00	100.00
US-400/US-69A & K-66	0.00	0.00	0.40	0.00	100.00
E. Jct. of US-77 & US-166	0.00	0.00	0.25	0.00	100.00
US-50 & US-77	3.00	0.00	0.40	0.00	100.00
Non-fatal Injury Crashes					
US-400 & K-47	10.00	4.00	4.26	0.94	6.15
US-400/US-69A & K-66	10.00	0.00	9.31	0.00	100.00
E. Jct. of US-77 & US-166	11.00	1.00	6.57	0.15	84.78
US-50 & US-77	11.00	2.00	9.60	0.21	79.17
Property-damage-only (PDO) Crashes					
US-400 & K-47	8.00	5.00	3.60	1.39	-38.89
US-400/US-69A & K-66	9.00	3.00	9.63	0.31	68.85
E. Jct. of US-77 & US-166	10.00	2.00	6.82	0.29	70.67
US-50 & US-77	6.00	7.00	6.30	1.11	-11.11

Table 4: Empirical Bayes Before-After Analysis for All Locations (Aggregated)

Crash Type	Observed Crashes (After)	Expected Crashes (After)	Percentage Change %	Odds Ratio	Unbiased Odds Ratio
Total	24.00	57.31	58.13	0.42	0.41
Fatal	0.00	1.22	100.00	0.00	0.00
Injury	7.00	29.74	76.47	0.24	0.23
Property-damage-only	17.00	26.35	35.49	0.65	0.63

The following assumptions were made in the EB analysis:

1. The TWSC intersections did not have any significant skew.
2. Except for the US-400 & K-47 intersection, the remaining three intersections had no left-turn lanes and no lighting during the before time period (the US-400 & K-47 intersection showed a left-turn lane on each major approach as well as lighting before conversion on Google Map Street View, imagery captured in November 2007).
3. All intersections were assumed to have no right-turn lanes and the local calibration factors (Cs) were assumed equal to 1.0.

Before-After Analysis of Fatalities and Injuries in Crashes

Table 5 presents the before-after analysis of fatality and injury rates at the four locations. Fatality and injury rates (on a per-year base) in all four locations were reduced after conversions to roundabouts. Fatality rates were reduced by 100% while injury rates were reduced by at least 60%. The analysis showed that severe crashes significantly decreased after the TWSC intersections were converted to roundabouts.

ECONOMIC EVALUATION – SAFETY BENEFIT

An important and a major component of the economic analysis is the avoided cost of crashes. Analysis in Tables 3 through 5 revealed a significant decline in crashes after conversion of the TWSC intersections on rural, high-speed roads to roundabouts at the four sites as a group. In particular, the number of crashes in the years after roundabout completion was well below expected crashes, based on crash rates in the periods before conversions to roundabouts. The decline was particularly pronounced among injury crashes, suggesting that the conversion to roundabouts was reducing both the number and severity of crashes. Such a change would generate significant economic value in terms of safety benefits. These benefits are estimated based on values presented in Table 1 and shown in Table 6.

The total value of the estimated 33.3 avoided crashes was $21.7 million. The value is large because the conversion to a roundabout helped reduce the severity as well as the number of crashes. For example, more than half of this amount, $12.8 million, resulted from avoiding 1.2 fatal crashes. The 33.3 avoided crashes were avoided at the four roundabouts over a three- or four-year post-roundabout construction period. Notice that the post-period crash data were collected for four years each at two of the intersections and for three years each at the other two intersections, resulting in a total of 14 year-intersections. Thus, the annual value of reduced crashes at a single intersection would be one-fourteenth as much, or $1.6 million ($21.7 million saved in total /14 year-intersections= $1.6 million per year per intersection). Considering the initial construction cost for one roundabout is around $3.0 million (according to Church 2007) (the construction costs for the US-50 & US-77

Table 5: Before-After Analysis of Death and Injury Rates (Per Year)

Location	Death Rate (Before)	Injury Rate (Before)	Death Rate (After)	Injury Rate (After)	Death Rate Change %	Injury Rate Change %
US-400 & K-47	0.60	5.80	0.00	2.33	-100.00	-59.77
US-400/US-69A & K-66	0.00	4.75	0.00	0.00	-	-100.00
E. Jct. of US-77 & US-166	0.00	5.00	0.00	0.33	-	-93.33
US-50 & US-77	1.00	7.00	0.00	0.50	-100.00	-92.86
All Sites	0.39	5.61	0.00	0.71	-100.00	-87.27

Table 6: Value of Avoided Comprehensive Crash Costs Over 3-4 Years

Crash Type	Observed Crashes (After)	Expected Crashes (After)	Reduction in Crashes	Comprehensive Crash Cost 2014	Crash Costs Avoided*
All Crashes	24.00	57.31	33.31	-	-
Fatal	0.00	1.22	1.22	$10,480,100	$12,785,700
Injury (Non-Fatal)	7.00	29.74	22.74	$385,600	$8,769,000
Property-damage-only	17.00	26.35	9.35	$10,900	$101,800
Total (4 intersections over 3-4 years)					$21,656,500

* The results of these economic estimates were based on the estimate of average economic costs on a per accident basis for each severity level for the year 2014, as shown in Table 1.

roundabout was $3.2 million; construction costs for another two similar roundabouts in Kansas that were not included in our study were $2.4 and $2.5 million), the savings of $1.6 million per year per intersection due to avoided crashes were significant. This result, however, depends to a significant degree on avoided fatal crashes at the roundabout. Six fatal crashes were reported at the TWSC intersections in the years before they were converted to roundabouts but none reported afterwards. Given the small number of intersections and fatal crashes involved, and comprehensive crash costs in excess of $10 million for each fatal crash, it is natural to wonder how much happenstance influenced the results. In particular, severe crashes may have occurred both before and after installation of the roundabout, but none were fatal after the roundabout was in use. This may reflect the relative safety of roundabouts but also may simply reflect chance. To address the latter possibility, Table 6 was revised by summing the fatal and non-fatal injury crashes to create a category for all injury crashes (fatal and non-fatal). The lower comprehensive crash cost in 2014 ($567,700, which was based on the value for 2000 and updated from 2000 to 2014 based on the change in the value of a statistical life, as shown in the last row of Table 1) for all injury crashes was utilized; Table 7 shows the results.

Table 7: Value of Avoided Comprehensive Crash Costs over 3-4 Years With Fatal and Non-Fatal Injury Crashes Combined

Crash Type	Observed Crashes (After)	Expected Crashes (After)	Reduction in Crashes	Comprehensive Crash Cost 2014	Crash Costs Avoided
All Crashes	24.00	57.31	33.31	-	-
Injury (Fatal and Non-Fatal)	7.00	30.96	23.96	$567,700	$13,601,500
Property-damage-only	17.00	26.35	9.35	$10,900	$101,800
Total (4 intersections over 3-4 years)					$13,703,400

The total estimated value from the 33.3 avoided crashes was $13.7 million. This translated into avoided crash costs of $1.0 million per year at each intersection ($13.7 million saved in total /14 year-intersections = $1.0 million per year per intersection). Therefore, the estimate of the annual reduction in comprehensive crash costs from conversion of TWSC intersections to roundabouts on rural high-speed roads was between $1.0 million and $1.6 million in 2014 dollars. Assuming a 20-year lifespan for a roundabout (based on FHWA 2010), the estimated monetary benefits due to avoided crashes were between $20.0 million and $32.0 million.

When interpreting these results, it is important to remember that safety benefits are just one of the components of economic benefits that can result from a transportation investment. The conversion of TWSC intersections to roundabouts could also result in a change in user costs such as travel time and vehicle operating costs and non-user costs such as vehicle emissions. The change in these costs would need to be included along with the estimated safety benefits in order to estimate comprehensive annual economic benefits from a roundabout intersection. Only such comprehensive annual benefits can be compared with costs as part of a benefit and cost analysis.

CONCLUSION AND DISCUSSION

Modern roundabouts provide an alternative to stop-controlled or signalized intersections; conversions of existing intersections to roundabouts continue across the U.S. While the safety benefits of converting traditionally controlled intersections to modern roundabouts in urban settings have been well-documented, conversions of TWSC intersections on rural, high-speed roadways to modern roundabouts have not been explored to the same extent. This study focused on the assessment of four rural high-speed approach TWSC intersections that were converted to roundabouts in Kansas. The evaluation procedures utilized were from the *Highway Safety Manual* (AASHTO 2010a). Economic evaluation was carried out to assess the monetary value of the safety benefits acquired.

Results of the analysis showed that, overall, all types of crashes were reduced after conversion of TWSC intersections to roundabouts. Total crashes decreased by 58.13%; fatal crashes were reduced by 100% at all locations; and non-fatal injury crashes were reduced with an overall reduction rate of 76.47%. Property-damage-only crashes were reduced by 35.49% as a whole, but two out of the four sites experienced increases in property-damage-only crashes after conversion to roundabouts. Based on the before-after analysis, fatality and injury rates were decreased at all four sites. In conclusion, the answer to the question "Are roundabouts on rural high-speed roadways safer than TWSC intersections?" is affirmative in our case, and that conversion of TWSC rural high-speed intersections to roundabouts provided similar safety benefits as their urban counterparts. The conclusions are consistent with previous studies on rural high-speed roundabouts.

Finally, to answer the question "What economic benefits can be expected for the conversion from TWSC intersections to roundabouts in terms of safety improvement?" the estimated safety benefits were significant in monetary terms. As in our case, the annual value of the reduction in comprehensive crash costs from conversion of a TWSC intersection on a rural, high-speed roadway to a modern roundabout was between $1.0 million and $1.6 million in 2014 dollars. Although it is too early to generalize this conclusion to all TWSC intersections, it should be reasonable for analysts and decision makers to expect parallel monetary benefits from converting rural high-speed approach TWSC intersections with similar traffic conditions and crash histories to modern roundabouts.

Although this paper accomplished its objectives of evaluating the safety benefits of rural roundabouts with high-speed approaches, the analysis is limited to the four intersections included in this study. The four sites may not be representative of all TWSC intersections in the U.S. with respect to traffic volumes and number of crashes. However, they should be representative of TWSC intersections with similar crash and traffic histories, design features, and driving behaviors. Studies based on larger datasets that include more qualified rural high-speed intersections are needed in the future to further testify to the safety performance of such roundabouts. On the other hand, for the safety benefit evaluation, the analysis relies on the average severity of non-fatal injury crashes that was utilized in AASHTO (2010b). A more precise estimate of safety benefits could consider the specific severity of non-fatal injury crashes reported at roundabouts and two-way-stop-controlled intersections. The severity might be expected to differ, particularly in light of the lesser severity of crashes in roundabouts observed in Table 4.

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