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Safety Impacts of Converting Stop-Controlled Intersections in Ottawa to Roundabouts

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Abstract **-** Roundabouts are becoming increasingly popular in North American road networks. They are used as a method for reducing traffic conflicts and enhancing road safety. This paper provides a statistical assessment of the impacts of roundabouts as modern safety treatment in the City of Ottawa. The assessment uses two statistical methods, which are Negative Binomial (NB) regression and Empirical Bayes (EB) before-and-after study to account for Regression to the Mean and time trend effects. The intersections within the City of Ottawa that were re-constructed as roundabouts within the period of 2012-2016 were taken as the study sample in this study. The results of the NB analysis showed significant *Roundabout* variable in total collisions, property damage only (PDO) collision severity and all collision impact type except for single motor vehicle (SMV) collisions. The results showed an increase in total, PDO, rear-end, and sideswipe collisions and decrease in angle collisions. The EB before-and-after study findings confirmed the increase in total, SMV, Sideswipe, rear-end and PDO collisions and the reduction of angle collisions, although the increase in SMV collisions was not statistically significant. The EB analysis also showed a 42% reduction in the number of injury+fatal collisions, which is very close to the estimated 48% reduction in angle collisions. In conclusion, this study shows an overall positive safety impact of roundabouts because of an approximately 42% reduction of the severe collisions that result in injury or fatality despite an increase of around 15% in the total number of collisions.

Keywords**:** Roundabouts, Traffic Safety, Empirical Bayes, Traffic Collision, Negative Binomial.

1 Introduction

Roundabouts, which are also referred to as modern roundabouts, are at-grade intersections with circular configurations that can move traffic safely and efficiently. The world's first modern roundabouts were designed and implemented in the UK in the 1960s and have become more common in Canada after their first implementation in the 1990s [1]. The channelized and curved approaches along with the circulatory path of roundabouts reduce vehicles' speeds, and the yield sign at each leg gives the right of way to circulating vehicles. In addition, the unidirectional movement of all vehicles on the roundabout reduces the number and severity of conflicts at the entrance to and exit from the intersection. The lower travelling speeds and reduced conflicts can substantially reduce the number of fatal and injury crashes [2].

Although the performance of roundabouts has been well-researched in Europe, there is relatively a lack of studies considering such factors as yearly changes in traffic trends and roundabout characteristics' effects on the safety performance of roundabouts in North America, including Canada. This paper aims to evaluate the safety effectiveness of roundabouts using a before-and-after study and regression analysis while accounting for analysis limitations such as Regression To the-Mean (RTM), yearly trends, and roundabout characteristics. The study was conducted in the City of Ottawa, Ontario, as a typical Canadian mid-size city.

2 Background

Given the diversity of reviews on roundabout safety performance evaluation, this section briefly reviews the research examining roundabout safety performance, crash characteristics, and other factors. The second edition of the roundabouts informational guide, published in 2010 as the National Cooperative Highway Research Program (NCHRP) Report 672, summarized the roundabout collision reduction effects but indicated that collision reductions are primarily favourable for single-lane, rural roundabouts [2]. Many studies used different statistical methods to evaluate the safety performance of roundabouts. De Brabander et al. [3] studied the safety impact of roundabouts on the number of collisions using before-and-after studies and the results indicated that roundabouts reduced the number of injury collisions by 34%. Recent research by Hu and Cicchino [4] studied the long-term collision counts and severity on roundabouts in Washington State using Poisson and Logistic regression models. The study found an 8.8% total collision reduction on double-lane roundabouts and an insignificant collision increase on single-lane roundabouts. Mamlouk and Souliman [5] studied 17 roundabouts in Arizona using collision rate analysis. The results showed a reduction in the number of total collisions on the single-lane but opposite effects on double-lane roundabouts. However, the collision severity was reduced for both single and double-lane roundabouts. Another study by Gbologah et al. [6] evaluated the safety performance of roundabouts in Georgia using the Empirical Bayes (EB) method. The results found 37% and 56% reduction in total and injury collisions, respectively.

This paper evaluates the safety performance of roundabouts located in Ottawa, Ontario, Canada as one of the new safety treatments implemented in the city while considering all the contributing factors such as yearly trends and roundabout characteristics. The Negative Binomial (NB) regression and EB before-and-after comparison are employed in this study to evaluate the safety effects of roundabouts on different collision types and severities.

3 Study Methodology

Two approaches were followed in the safety analysis of roundabouts using collision records, namely NB regression analysis and EB before-and-after study. Both methods attempt to estimate the changes in safety levels where a treatment has been implemented. The following sections explain the process used in this study to apply each method.

3.1 NB Regression Approach

The first statistical approach of safety data was NB regression, which attempted to establish a safety performance function (SPF) or a relationship between annual collision frequency and the intersection characteristics of the roundabouts considered in the study. The independent variables included the natural logarithm of traffic volume as the main exposure variable, other intersection characteristics, and a dummy variable for the presence of roundabouts. In addition, because collision frequencies corresponded to different years, a dummy variable was considered for each year, with 2010 used as a reference year, to account for the potential of annual variation in collision frequencies. The regression was attempted for different collision categories to examine the effect of roundabouts on each collision category depending on the collision impact type or severity level. The format of the models is shown in the following equation.

$$Annual\ Collision\ Frequency = exp[\beta_0 + \beta_1(Roundabout) + \beta_i(X_i)] \quad (1)$$

Where β_i= regression coefficients; $Roundabout$ = dummy variable for the presence of a roundabout (1 for roundabout or 0 otherwise); and X_i = other independent variables such as traffic volume or speed.

The Akaike Information Criterion (AIC) was used as a measure of goodness of fit to compare the different models. Independent predictors that were not significant at a 10% level of significance were removed from the model using stepwise regression with backward elimination. Regression attempts that did not produce independent significant variables were also checked using manual forward stepwise regression at the same level of significance. First, for each collision category, a model was developed with the total average annual daily traffic (AADT) on both intersecting roads as the exposure variable. Then, another model was also developed with AADT on each intersecting road as a separate independent variable. The two models were compared using the models' AIC values, and the model with the lower AIC value was selected as the final SPF. As mentioned earlier, all AADT variables were taken as the natural logarithm of AADT, i.e., $ln(AADT)$, so that the model would yield zero predicted collisions at zero traffic volume. The NB regression was performed by STATA 16 software.

3.2 EB Before-and-After Study

The second approach used in this paper for the analysis of roundabouts' safety performance was the EB before-and-after study. This method was developed by Hauer [7] and has been well documented in the Highway Safety Manual (HSM) [8]. It has been commonly used in safety assessment as it accounts for regression-to-the-mean (RTM) effects and changes in traffic flow and other trends over time. Hauer [7] showed that the change (δ) in the safety level of treatment could be determined as:

$$\delta = \pi - \lambda \tag{2}$$

Where δ = change in safety due to the treatment; π = expected number of collisions in the "after" period if the treatment had not been installed; and λ = observed number of collisions in the "after" period with the treatment in place.

Safety effectiveness can also be assessed using the index of effectiveness (θ), which is calculated as follows:

$$\theta = \frac{\frac{\lambda}{\pi}}{1 + \frac{VAR(\pi)}{\pi^2}} \tag{3}$$

Where $Var(\pi)$ = variance of the estimate of the expected number of collisions in the "after" crashes had no improvement been made.

The EB method details the process to estimate the expected number of collisions (π) by combining the predicted number of collisions in the "after" period if treatment is not implemented using a SPF and the observed number of collisions in the "before" period. In the case that δ and θ are positive and less than one, respectively, it can be concluded that the treatment has a positive effect on the safety performance. Finally, it is noted that the SPF used in this method is developed following a similar approach to the NB regression. However, the SPF used in the EB before-and-after study is developed for the reference group, which in this case is made of four-way stop-controlled intersections, and the "before" period of roundabouts sites.

4 Study Area and Data Collection

The data required for safety analysis based on NB regression and EB before-and-after study included collision and traffic volume data on roundabouts in the City of Ottawa and on a representative reference group. Also, for the EB before-and-after study, the data were required on the roundabout intersections before and after treatment, which is the conversion of the intersections to roundabouts. The following sections present the study area and data collection processes followed in this study.

4.1 Study Area and Site Selection

This study was performed in Ottawa, Ontario, Canada, which currently has 21 roundabouts as listed on the City of Ottawa website. The roundabouts constructed between 2012-2016 were selected for the collision-based statistical analysis in this study to have at least three full years of collision data after the roundabout construction and prior to COVID-19 public health restrictions in 2020. As a result, a total of 13 roundabouts that fit this criterion were selected for the analysis. Before the roundabout construction, 12 sites were stop-controlled intersections and only one was a signalized intersection. Therefore, only the 12 sites which were originally stop-controlled were selected as the treated sites.

Figure 1 shows the locations of roundabouts in the City of Ottawa. For comparison, a reference group of ten intersections was selected and is referred to as the reference group or untreated sites. Because majority of the roundabouts in Ottawa are either new intersections or re-construction of existing stop-controlled intersections, the reference group was selected as stop-controlled intersections. These untreated sites were selected such that they have similar traffic volumes, road classifications, and approach speeds as the treated sites before the treatment and would also be in the same wards as the roundabouts.

The number of selected treated and reference groups along with the road classification of the major and minor roads is presented in Table 1. The dominant group of roundabouts within Ottawa is the one-lane roundabouts with collector and local road classifications.

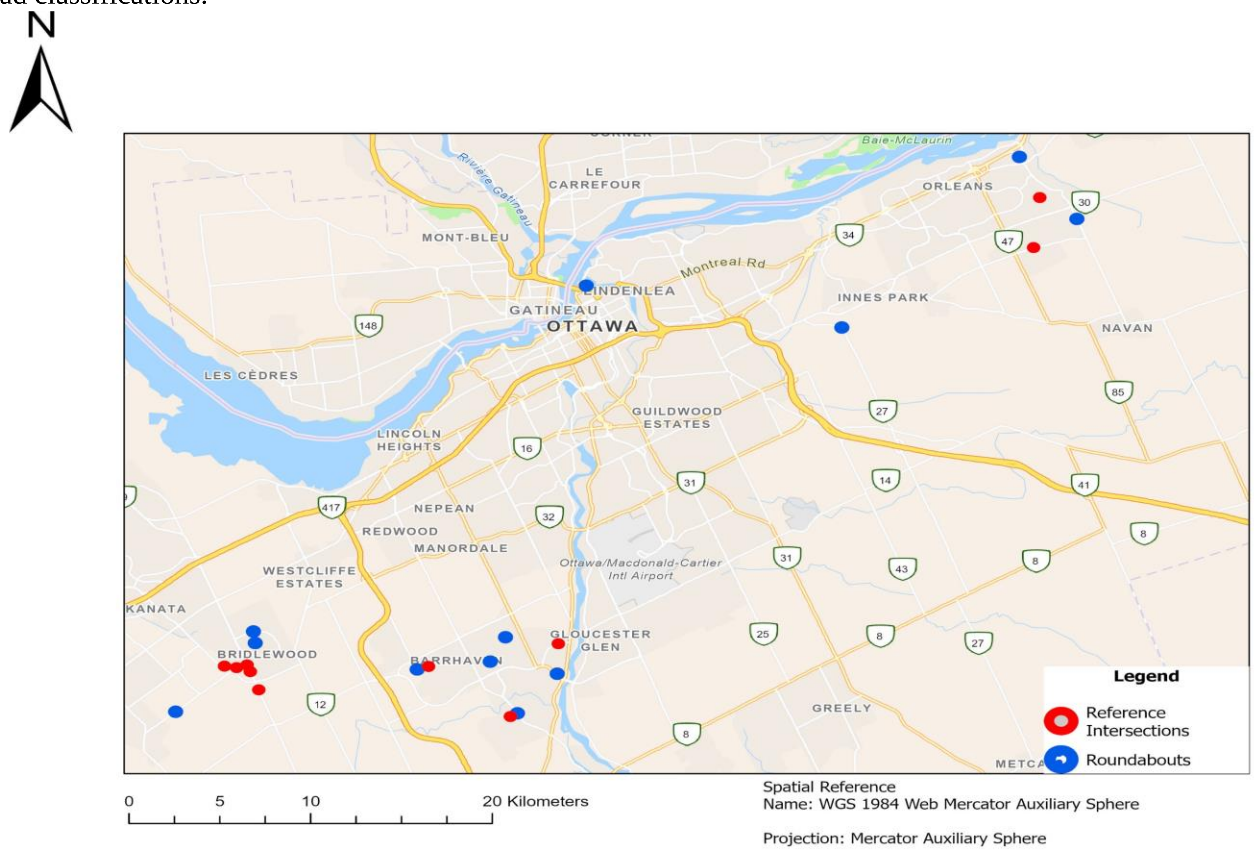

Figure 1: Selected Roundabout and Reference Group Sites.

Table 1: General Characteristics of the Selected Roundabouts and Reference Group.

	Number of Sites		Classification of the Intersecting Roads				
			Arterial-Arterial	Arterial-Collector	Arterial-Local	Collector-Collector	Collector-Local
Roundabouts (treated sites)	2 Lane	2	2	3	1	4	2
	1 Lane	10					
Reference group (untreated sites)	10		1	3	3	1	2

4.2 Data Collection

For safety analysis using NB regression and EB before-and-after study, six years of collision data were collected for each roundabout, corresponding to three years before and three years after the treatment or roundabout construction date while excluding the construction year itself. Similarly, three years of collision and traffic volume data were collected at each intersection in the reference group. These data were collected from the Open Ottawa data source [9] and the city of Ottawa Traffic Department as shapefiles that can be imported into ArcGIS pro software. The traffic volumes on the intersecting roads at each site were obtained as 8 to 12 hours traffic count studies and were converted to AADT using conversion factors used by the City of Ottawa. AADT was thus estimated for the two intersecting roads (referred to as major and minor roads based on their road classification or traffic volume if they belong to the same classification), and the sum is used as the total intersection traffic volume.

The collision data were identified based on a 50-m buffer zone for each intersection location, measured from the intersection's centre, and were classified as intersection-related collisions. The collision data were categorized into four impact types, which are rear-end, angle, single motor vehicle (SMV), and sideswipe. The collisions were also classified based on their severity as property damage only (PDO), injury, and fatal. Finally, the posted speed limits on the intersecting major and minor roads for each intersection were also extracted from ArcGIS pro software based on the road details shapefiles, which had such details as speed, road classification and the number of lanes for each road.

5 Analysis and Results

This section begins with NB regression results based on the SPFs developed for Ottawa's local conditions. The last part provides the EB before-and-after study results using SPF models developed for the reference sites and roundabout intersections "before' treatment.

5.1 NB Regression

In this section, NB regression models were fitted for the different collision categories based on severity and impact type. The sites considered in this analysis were the treated sites in both periods before and after treatment. Table 2 shows the final SPFs or regression models for each collision category, where the dependent variable is the annual number of collisions at an intersection. As shown in the table, the total traffic volume on the two intersecting roads, $ln(AADT)$, or the traffic volume on the major road, $ln(AADT_{major})$, was a significant independent variable for all collision categories except for SMV collisions. The lack of significant relationship to traffic volume as the exposure factor is likely a result of the low numbers of SMV collisions at each site. As shown in Table 2, all collision categories except for SMV collisions and severe collisions (injury+fatal) have the $Roundabout$ variable as a significant independent variable in their models. However, for rear-end collisions, the model with lowest AIC value did not have $Roundabout$ as a significant variable but the difference between this lowest AIC value and the model in Table 2 is only 2.4%.

As shown in Table 2, the variable $Roundabout$ has a positive regression coefficient of 0.79 and 0.78 in total and PDO collisions. These models mean that a roundabout would experience around 120% and 118% increase in total and PDO collisions, respectively. On the other hand, the $Roundabout$ variable was found to be significant in collision impacts of rear-end, sideswipe and angle with the coefficient of 1.19, 1.59 and -0.55 respectively, suggesting 390% and 490% increase in rear-end and sideswipe collisions and 42% decrease in angle collisions on roundabouts compared to the reference case of a stop-controlled intersection.

Table 2: Final SPFs for the Different Collision Categories (Treated Sites in the Before and After Periods).

Collision category	Variable	Regression coefficient	p-value	Dispersion factor
Total	ln(AADT_major)	0.080	<0.001	0.487
	Speed_minor	0.018	0.084	
	Roundabout	0.791	0.002	
	Constant	-7.124	<0.001	
Rear-end	Roundabout	1.186	0.027	1.368
	ln(AADT_major)	1.547	<0.001	
	Constant	-14.041	<0.001	
Angle	ln(AADT_total)	1.680	<0.001	0.281
	Speed_minor	-0.030	0.059	
	Roundabout	-0.550	0.069	
	Y2018	1.675	0.094	
	Constant	-13.905	<0.001	
Sideswipe	ln(AADT_total)	2.523	0.016	3.404
	Roundabout	1.589	0.094	
	Constant	-26.367	0.008	
SMV1	Y2014	0.815	0.028	0
	Y2017	1.066	0.006	
	Constant	-0.814	<0.001	
PDO	Roundabout	0.776	0.004	0.408
	ln(AADT_major)	0.833	<0.001	
	Speed_minor	0.021	0.038	
	Y2012	-0.943	0.046	
	Constant	-7.693	<0.001	
I+F	ln(AADT_total)	0.741	0.062	1.428
	Y2012	1.089	0.083	
	Constant	-8.072	0.029	

$AADT$ = total AADT, equal to the sum of AADT for the intersecting roads (veh/d); $AADT_{major}$ = AADT on the intersection's major road (veh/d); $Speed_{minor}$ = speed limit on the intersection's minor road (km/h); and Y20xx = dummy variables for the years 20xx, respectively.

5.2 EB Before-and-After Study Results

As mentioned, the EB before-and-after study uses SPF models developed in a similar approach to NB regression while considering the collision data for the reference group and the treated sites only in the period before treatment, which are shown in Table 3. Then, the expected number of collisions on each roundabout in the treated group was estimated in each year of the "after" period using the SPF models and the collision frequencies before treatment.

The SPF model outcomes were checked for overestimation or underestimation of the results. For example, the rear-end collisions model with the lowest AIC value was found to overestimate the predicted number of collisions on many sites compared to the actual number of collisions observed at these locations. Therefore, a model with slightly higher AIC value (1.8% difference) was selected. Table 4 summarizes the results and shows the total number of collisions for all 12 roundabouts in the treated site's group, observed collisions, change in collision frequency, and index of effectiveness.

Table 3: Final SPFs for the Different Collision Categories (Reference Group and Treated Sites in the Before Period).

Collision Category	Variable	Regression Coefficient	*p*-value	AIC
Total Collisions	$ln(AADT)$	0.808	<0.001	240.02
	Constant	-6.596	0.002	
Rear-End Collisions	$ln(AADT_{major})$	2.851	<0.001	139.64
	Y2019	1.125	0.021	
	Constant	-25.899	<0.001	
Angle Collisions	$Speed_{minor}$	-0.062	0.006	172.13
	$ln(AADT_{major})$	1.867	<0.001	
	Y2017	-1.309	0.022	
	Constant	-13.206	<0.001	
Sideswipe Collisions	Constant	-2.433	<0.001	34.79
SMV Collisions	Y2014	1.609	0.004	87.58
	Constant	-1.321	<0.001	
PDO	$ln(AADT_{major})$	0.946	<0.001	204.38
	Y2012	-0.805	0.073	
	Constant	-7.670	0.001	
Injury + Fatal Collisions	Y2012	1.252	0.023	127.54
	Y2019	1.252	0.018	
	Y2018	1.134	0.037	
	Constant	-1.252	<0.001	

No traffic volume variable was significant in SMV, sideswipe, and injury+fatal collisions model at 10% level of significance.

Table 4: Summary of EB Before-and-After Study Results.

Collision category	π	λ	δ	θ	95% Confidence interval for θ	
Total	94.5	109	-14.5	1.15	1.12	1.18
Rear-end	18.5	31	-12.5	1.64	1.49	1.79
Angle	63.1	33	30.1	0.52	0.48	0.55
Sideswipe	2.2	20	-17.8	8.00	5.88	10.16
SMV	21.0	25	-4.0	1.14	0.97	1.31
PDO	70.9	98	-27.1	1.37	1.33	1.41
I+F	18.7	11	7.7	0.58	0.47	0.69

π = number of expected collisions "after" period if the treatments would have not been installed; λ = number of observed collisions "after" the roundabout's installation; δ = difference between expected and observed collisions during the "after" period; and θ = roundabout index of effectiveness.

As shown in Table 4, the negative differences between expected and observed collisions during the "after" period (negative values of δ) and the θ values greater than 1.0 indicate an increase in the expected number of collisions for the categories of total collisions and the collision impacts of SMV, rear-end, SMV, sideswipe, and PDO collisions. On the other hand, angle and injury+fatal collisions have positive values of δ and θ values that are less than 1.0 indicating a reduction in these collision categories. The 95% confidence interval for the θ value of each collision category indicates that these values are statistically significant at a 5% level of significance except for SMV collisions. Specifically, the θ value of 0.58 for injury+fatal collisions indicates a 42% reduction in injury and fatal collisions at the intersections after conversion to roundabouts. This reduction is close to the 48% reduction in angle collisions, which are normally more likely to result in injury or fatality.

6 Conclusions

This paper evaluated the safety level of roundabouts through a statistical analysis of historical collision records on twelve intersections in the City of Ottawa that were re-constructed as roundabouts in the period between 2012 to 2016. Two statistical methods were employed, which are the NB regression and EB before-and-after study. The results of both methods an increase in the total number of collisions on roundabouts compared to the reference case of a stop-controlled intersection. According to both methods, this increase is likely a result of increasing collisions of specific impact types such as rear-end, sideswipe, and SMV collisions, all of which are more likely to produce PDO collisions. Therefore, PDO collisions were also found to increase on roundabouts compared to the reference case. On the other hand, both methods indicated a considerable reduction in angle collisions, which are more associated with severe collisions. Therefore, the EB analysis also showed a considerable reduction in the number of collisions resulting in injury or fatality. It is noted though that the NB method did not indicate this reduction in the collisions resulting in injury or fatality, which is likely caused by the relatively low numbers of injury and fatal collisions.

It is notable that the EB before-after method results have provided more comprehensive results as it considers the effects related to regression to the mean, traffic volume trends and all other uncontrolled variables which were not considered in the models. As the NB models are not considering the RTM and yearly changes in trends, the results of NB models may either overestimate or underestimate the effects of roundabouts, this can justify the NB results are considerably different than EB models.

This study can be improved by increasing the number of treated sites, which was not possible at the time of this study based on the number of available sites with enough collision history outside the period of reduced traffic volumes due to COVID-19 restrictions. As Canadian cities implement more roundabouts, the study can be repeated to increase the reliability of the finding. When a larger sample is available for analysis, parameters such as the specific geometric characteristics of the roundabout can be included in the SPFs. Finally, it is recommended to complement this study with an examination of the driver behavior on roundabout intersections to assess the conflicts arising between different vehicles as they enter and exit the roundabouts and assess the speed behavior. This assessment would allow for understanding of why specific types of collisions may increase or decrease on roundabouts compared to other intersection types.

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