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Investigating Pedestrian Injury Crashes on Modern Roundabouts in Addis Ababa, Ethiopia

Getu Segni Tulu
PhD Student
Centre for Accident Research and Road Safety - Queensland (CARRS-Q),
Queensland University of Technology
Brisbane QLD 4059, 130 Victoria Park Road
Kelvin Grove 4059 (Brisbane)
Tel: +61 7 31380526
E-mail getu.tulu@student.qut.edu.au or getusegne@yahoo.com

Md. Mazharul Haque*
Lecturer
Centre for Accident Research and Road Safety (CARRS-Q), Faculty of Health and
Civil Engineering and Built Environment, Science and Engineering Faculty
Queensland University of Technology
130 Victoria Park Rd
Kelvin Grove QLD 4059 Australia
Tel: +61 7 3138 4511
Email: m1.haque@qut.edu.au

Simon Washington
Professor
Civil Engineering and Built Environment, Science and Engineering Faculty and
Centre for Accident Research and Road Safety (CARRS-Q), Faculty of Health
Queensland University of Technology
2 George St GPO Box 2434
Brisbane QLD 4001 Australia
Tel: +61 7 3138 9990
Email: simon.washington@qut.edu.au

Mark J. King
Senior Lecturer
Centre for Accident Research and Road Safety-Queensland (CARRS-Q)
Queensland University of Technology (QUT)
K Block K433, Victoria Park Road
Kelvin Grove 4059 (Brisbane)
Queensland, Australia
Tel: +6173138 4546
E-mail: mark.king@qut.edu.au

*Corresponding Author

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ABSTRACT

Pedestrian crashes are one of the major road safety problems in developing countries representing about 40% of total fatal crashes in low income countries. Despite the fact that many pedestrian crashes in these countries occur at unsignalized intersections such as roundabouts, studies focussing on this issue are limited—thus representing a critical research gap. The objective of this study is to develop safety performance functions for pedestrian crashes at modern roundabouts to identify significant roadway geometric, traffic and land use characteristics related to pedestrian safety. To establish the relationship between pedestrian crashes and various causal factors, detailed data including various forms of exposure, geometric and traffic characteristics, and spatial factors such as proximity to schools and proximity to drinking establishments were collected from a sample of 22 modern roundabouts in Addis Ababa, Ethiopia, representing about 56% of such roundabouts in Addis Ababa. To account for spatial correlation resulting from multiple observations at a roundabout, both the random effect Poisson (REP) and random effect Negative Binomial (RENB) regression models were estimated and compared. Model goodness of fit statistics reveal a marginally superior fit of the REP model compared to the RENB model of pedestrian crashes at roundabouts. Pedestrian crossing volume and the product of traffic volumes along major and minor road had significant and positive associations with pedestrian crashes at roundabouts. The presence of a public transport (bus/taxi) terminal beside a roundabout is associated with increased pedestrian crashes. While the maximum gradient of an approach road is negatively associated with pedestrian safety, the provision of a raised median along an approach appears to increase pedestrian safety at roundabouts. Remedial measures are identified for combating pedestrian safety problems at roundabouts in the context of a developing country.

Keywords: Pedestrian safety; Random effect Poisson model; Pedestrian exposure; Spatial factors; Addis Ababa, Ethiopia

INTRODUCTION

Modern roundabouts have been introduced in Addis Ababa in recent years, although the provision of traffic circles for circulating traffic at intersections has been in practice for the last 30 years [1]. A modern roundabout has four main characteristics that can distinguish its traffic operation from traffic circles [2]. First, a roundabout has yield control upon entry to all approach legs, while a traffic circle has no yield control upon entry. Second, priority is given to circulating traffic in case of modern roundabouts while traffic circles have no provision for priorities; hence a roundabout has less conflicting vehicle movements. Third, a vehicle turning left (note that driving is undertaken on the right side of the road in Ethiopia) needs to navigate counter-clockwise around the central island to make the turn in a roundabout, while a traffic circle may allow for vehicles to travel left of the central island to make a left turn. Fourth, pedestrian access and crossings are only allowed before the yield line of an approach to a roundabout; in contrast, a traffic circle may permit pedestrians to access the central island for crossing.

Research suggests that modern roundabouts have been successful in reducing the number of traffic crashes and the severity of injuries in many cases in developed countries [e.g., 3, 4-6]. For instance, installation of modern roundabouts contributed to a reduction of 31% to 73% injury crashes at installed intersections in the United States[7]. A before-after study by Persaud, Retting, Garder, & Lord [8] reported that replacing 24 stop-controlled and signalized intersections with modern roundabouts resulted in a 39% reduction in total crashes and a 76% reduction in injury crashes. A comprehensive review of non-US studies also showed installation of modern roundabouts led to about a 30-50% reduction in injury crashes and a 50-70% reduction in fatal crashes[9]. A general conclusion from these studies is that improved geometric configuration and reduced approaching speeds due to deflected geometry along the approach to a roundabout reduce the likelihood and the severity of injury crashes at roundabouts.

Although modern roundabouts have been found to improve operational efficiency and safety performance in developed countries[e.g., 10], the safety of modern roundabouts in the context of developing countries has yet to be examined. There are many differences in roadway and geometric characteristics, enforcement schemes, presence of roadway furniture, pedestrian crossing facilities, and driver and pedestrian behaviour in developing countries compared to developed countries. A recent study [11] comparing the pedestrian crash risk in developing and developed countries has identified several significant differences that are responsible for the elevated crash risk of pedestrians in a developing nation. Critical factors include illegal crossing, walking along the road, walking while impaired (e.g. by alcohol), high annual growth of motorisation, poor maintenance of vehicles, lack of proper road safety education and poor traffic enforcement. Akloweg, Hayshi, & Kato [12] have reported that about 65% of the vehicle population in Addis Ababa is more than 15 years old and unroadworthiness of these vehicles might contribute to lower levels of safety. Given these differences in roadway, traffic, vehicle and behavioural characteristics, the presumption that pedestrian safety at roundabouts will be the same when they are transferred from developed nations to a developing country, merits a rigorous investigation.

Pedestrian injury crashes represent nearly 85% of the total injury crashes in Addis Ababa[13, 14]. A recent study shows that pedestrian injuries at intersections are more severe than midblock crashes in Addis Ababa[15]. The provision of a roundabout may help reduce pedestrian injuries at high risk intersections for two reasons. First, a roundabout reduces the conflict points at an intersection significantly. For instance, a four-legged intersection has 32 vehicle–vehicle conflict points which can be reduced to 8 conflict points if the intersection is converted into a single-lane roundabout. Second, the deflected geometry of the approaches and defined priority rules among road users generally encourage drivers to reduce speeds while approaching the roundabout, which in turn reduces crash risk and injury severity. Many studies [e.g., 16, 17-19] have also reported that the safety performance of roundabouts varies according to their geometric features, operating speed and traffic flows. However, the influences of operating speed and various geometric factors such as gradient of approach roads and presence of divider or median on pedestrian crashes at modern roundabout have not been investigated thoroughly—hence maximum gradient—which reflects the extreme of performance required of drivers, was used as a model variable. In addition to these factors, the safety performance of a roundabout may be affected if there are additional influences from land use characteristics and road users. For instance, many roundabouts in Addis Ababa are installed near public transport terminals to facilitate traffic around the terminal. Public transport terminals in a developing country are usually associated with increased pedestrian crossing movements, and also attract many road side activities such as hawkers on the footpaths along surrounding roads. This pattern is seen in many developing countries and may introduce additional challenges for pedestrian safety around roundabouts. Therefore the generation of safety performance functions for recently installed modern roundabouts in Addis Ababa may help to develop insights into pedestrian safety problems at roundabouts in developing countries in general and in Addis Ababa in particular.

As such, the objective of this study was to develop and evaluate crash prediction models of pedestrian crashes at roundabouts so that significant geometric, traffic and land use characteristics affecting pedestrian safety could be identified and potential remedial measures could be taken to combat pedestrian safety problems at roundabouts. The contribution of this study is threefold. First, it examines the pedestrian safety issue in a developing country. This is significant because pedestrian fatalities in low income countries, which are found mostly in Africa, represent nearly 40% of total fatal crashes in these countries[11, 20], while studies focusing on specific pedestrian safety problems in developing countries are few. Second, this study develops new insights into pedestrian safety around modern roundabouts in a developing nation setting which will be helpful for transport practitioners seeking to develop countermeasures to combat existing safety problems as well as to design new roundabouts. A safety performance function for pedestrian crashes at roundabouts in a developing country represents a unique contribution to the road safety literature. Third, the safety performance function of this study aimed to include many unique spatial variables collected with pedestrian behaviour in developing country setting in mind, in addition to common geometric, roadway and traffic factors.Thus,it is likely to provide a better model estimate and better insights into the pedestrian safety problems at roundabouts. Many studies developing a road safety performance function for a transport facility like an intersection or roundabout often exclude these spatial variables due to data collection difficulties, and as a result suffer from omitted variable bias[21].

The remainder of the paper first includes a description of the statistical models employed to develop and test safety performance functions for pedestrian crashes at roundabouts, briefly describing random effect Poisson (REP) and random effect negative binomial models (RENB) that can take into account temporal correlations resulting from multiple observations at a site. The Data Description section describes a variety of exposure information, geometric, traffic and land use characteristics variables collected for analysis of this study. The results of the statistical models are then discussed, followed by overall research conclusions.

METHODOLOGY

Model Development

Crashes occurring on transport facility locations such as roundabouts are often approximately Poisson or Negative Binomial (NB) distributed, thus requiring the appropriate regression model to relate covariates to crash outcomes [22]. The NB model overcomes the 'mean equal to variance' assumption of the Poisson regression model and is generally preferable since overdispersion is often present in motor vehicle crash count data.

Let Y_{it} is the number of pedestrian crashes at i^{th} roundabout and t^{th} time period, and Y_{it} is Poisson distributed and independents over all roundabouts and time periods such as

$$Y_{it} \mid \mu_{it} \sim Poisson(\mu_{it}), \qquad i = 1, 2, \ldots\ldots, I \text{ and } t = 1, 2, \ldots\ldots, T \tag{1}$$

where μ_{it} is the Poisson mean for i^{th} roundabout and t^{th} time period. In the Poisson regression model, the expected number of crashes is modelled as follows [22]:

$$\mu_{it} = \exp(\mathbf{X}_{it}{}'\boldsymbol{\beta}) \tag{2}$$

where $\mathbf{X}_{it} = (1, X_{it,1}, \ldots\ldots, X_{it,k})'$ is a vector of covariates representing roundabout-specific attributes and $\boldsymbol{\beta} = (\beta_0, \ldots\ldots, \beta_k)'$ is a vector of unknown regression parameters. To account for overdispersion in the crash data, the NB model accommodates a stochastic component to the mean function of the above Poisson regression model as follows[23]

$$\mu_{it} = \exp(\mathbf{X}_{it}{}'\boldsymbol{\beta} + \varepsilon_{it}) \tag{3}$$

where ε_{it} is the model error that is independent of all covariates. The NB model assumes that $\exp(\varepsilon_{it})$ is gamma distributed as $Gamma \sim (\phi, \phi)$ with mean 1 and variance $1/\phi$ for all i and t (with $\phi > 0$). The inverse of dispersion parameter, ϕ allows accommodatingoverdispersion in the crash data. The mean structure of the above formulation of the NB model is simplistic and does not take into account possible nonlinear relationships between traffic flows and crashes. Numerous studies [e.g., 21, 24, 25] have adopted logarithmic transformation of major and minor road traffic flows to develop safety performance functions for intersection crashes. Guided by prior research, the mean of pedestrian crashes at roundabouts of this study is structured as follows:

$$\mu_{it} = \alpha_0 (AADT_i^{major} \times AADT_i^{minor})^{\alpha_1} (ADPCV_i)^{\alpha_2} \exp(\mathbf{X}_{it}{}'\boldsymbol{\beta} + \varepsilon_{it}) \tag{4}$$

where $AADT_i^{major}$ and $AADT_i^{minor}$ are respectively major and minor road traffic flows for roundabout i; $ADPCV_i$ is the average daily pedestrian crossing volume for roundabout i; α_0, α_1 and α_2 are regression parameters to be estimated.

There are various sources of heterogeneity in crash data, including uncertainty in exposure and covariates, omitted variables, model misspecification, data clustering, and unaccounted temporal correlation. The above negative binomial regression model may not be appropriate for time-series cross-section panel data as it does not take into account location-specific effects. Without accounting for location-specific effects and potential serial correlation, the estimated standard errors of regression coefficients may be underestimated and resulting inferences may be misleading [22, 26]. To account for structured heterogeneities introduced by data collection and the clustering process, two slightly different random effect models are employed to model pedestrian crashes at roundabouts. These are the Random Effect Poisson (REP) model, and the Random Effect Negative Binomial (RENB) model.

Random Effect Poisson (REP) model

To account for location-specific effects and structured heterogeneity, the REP model replaces the model error term (ε_{it}) of Eq. (4) by a location-specific random effect δ_i as follows [27]

$$\begin{aligned} \mu_{it} &= \alpha_0 (AADT_i^{major} \times AADT_i^{\min or})^{\alpha_1} (ADPCV)^{\alpha_2} \exp(\mathbf{X}_{it}{}' \boldsymbol{\beta} + \delta_i) \\ \gamma_i &= \exp(\delta_i) \\ \gamma_i &\sim Gamma(\varphi, \varphi) \end{aligned} \tag{5}$$

The above specification assumes that the effects of covariates on pedestrian crashes at roundabouts are the same but the intercept is different across roundabouts. The location-specific effect δ_i accommodates a correlation among multiple observations from a roundabout in that the observations within a roundabout are exchangeable and hence the correlation is constant between any two observations within a roundabout. Therefore the above REP model resembles a Generalized Estimation Equation model from the Poisson distributional family with exchangeable correlation.

Random Effect Negative Binomial (RENB) Model

The RENB model[28] assumes that the number of crashes at a roundabout*i* for a given year *t*, i.e. n_{it} is independently and identically distributed with parameter $\nu_i \mu_{it}$ and ψ_i, where ν_i is the location-specific random effect and μ_{it} is the expected mean of pedestrian crashes at roundabouts as specified in Eq. (4). Thus the mean of n_{it} is $\nu_i \mu_{it} / \psi_i$ and the variance is $(\nu_i \mu_{it} / \psi_i) / z$, where $z = 1/(1 + \nu_i / \psi_i)$. To account for the location-specific effect, the RENB model assumes the parameter z to be a beta distributed random variable with distributional parameter (*a, b*). The probability density function of the RENB model for the i^{th} roundabout can be expressed as[29]

$$\mathrm{P}(\mathrm{n}_{\mathrm{i1}},\ldots.\mathrm{n}_{\mathrm{iT}}|\mathrm{X}_{\mathrm{i1}},\ldots\ \mathrm{X}_{\mathrm{iT}}) = \frac{\sqrt{\mathrm{a+b}}\sqrt{\mathrm{a}+\sum_{\mathrm{T}}\mu_{\mathrm{it}}}\sqrt{\mathrm{b}+\sum_{\mathrm{T}}\mathrm{n}_{\mathrm{it}}}}{\sqrt{\mathrm{a}}\sqrt{\mathrm{b}}\sqrt{\mathrm{a+b}+\sum_{\mathrm{T}}\mu_{\mathrm{it}}+\sum_{\mathrm{T}}\mathrm{n}_{\mathrm{it}}}} \prod\nolimits_{\mathrm{T}} \frac{\sqrt{\mu_{\mathrm{it}}+\mathrm{n}_{\mathrm{it}}}}{\sqrt{\mu_{\mathrm{it}}}\sqrt{\mathrm{n}_{\mathrm{it}}+1}} \tag{6}$$

The above NB model accounts for unobserved heterogeneity across locations and time by specifying the overdispersion parameter as randomly distributed across groups. This RENB model is similar to a Generalized Estimation Equation model with Negative Binomial distributional family and exchangeable correlation across multiple within-roundabout observations.

Model Evaluation and Selection Criteria

The REP and RENB models of pedestrian crashes at roundabouts use roadway geometry, traffic variables and land-use characteristicsas potential covariates. The models are estimated using the Maximum Likelihood (ML) algorithm, while Akaike's Information Criterion (AIC) and the Bayesian Information Criterion (BIC) have been used to compare the performance of these models in estimating pedestrian crashes at roundabouts. The AIC provides an assessment of model fitness by using the maximum likelihood at convergence penalized by the number of parameters used to calibrate the model as follows [30]:

$$AIC = 2k - LL(\boldsymbol{\beta}) \tag{7}$$

where k is the total number of estimated parameters in a model and $LL(\boldsymbol{\beta})$ is the log-likelihood of the estimated model. AIC thus captures the maximum variability explained by the parameters in a model after penalizing for a higher number of parameters in the model. A similar goodness of fit criterion is the BIC [31] that weighs the trade-off between model accuracy and model complexity as follows:

$$BIC = -2LL(\boldsymbol{\beta}) + k * \log_e(n) \tag{8}$$

where$n$ is the number of observations used to estimate the model. From the above two equations, it is clear that the penalty for the number of parameters in a model is larger in BIC than AIC. A model with lower AIC or BIC value is generally preferred.

Parameter Effects

Incidence rate ratios (*IRR*) have been computed to interpret the effect of each significant variable included in the model [27, 28]. The *IRR*, or $\exp(\beta)$, provides an estimate of the impact of an explanatory variable on the expected pedestrian crash frequency for a one unit change in a continuous variable or the factor change of a categorical variable. If the *IRR* of an explanatory variable is greater than 1, an increase or factor change in that variable results in an increase in pedestrian crashes at roundabouts. Conversely, a reduction of pedestrian crashes at roundabouts corresponds to an *IRR* that is less than 1.

DATA DESCRIPTION

To establish a safety performance function for pedestrian crashes at roundabouts, data were collected from a total of 22 modern roundabouts in Addis Ababa, Ethiopia. These 22 roundabouts were randomly selected from all of the modern roundabouts in Addis Ababa using a randomly assigned draw number. These modern roundabouts account for about 56% of such roundabouts in Addis Ababa. All the roundabouts were at-grade unsignalized intersections, of which 14 were four-legged roundabouts and 8 were three-legged roundabouts. A roundabout pedestrian crash was defined as any pedestrian crash occurring at the roundabout or within 50m of the roundabout along major and minor roads. Detailed records of pedestrian crashes were collected from the Addis Ababa Police Commissioner's office and records of pedestrian injury crashes were collected from the sub-city Police departments. Two hundred and fifty six pedestrian crash counts over three years from 2010 to 2012 at the selected roundabouts were included in the model. The data from this period were deemed to be accurate yet also reflect fairly static conditions at the sites. A typical year was divided into three four-month time periods based on the climate, traffic and pedestrian flows [32]. The four-month intervals were June-September, October-January and February-May. To account for seasonal variations, pedestrian crashes at each roundabout were counted in these four-month intervals. Explanatory variables like exposure information, roadway and traffic variables, and spatial characteristics of the selected roundabouts were also collected for these four-month intervals from 2010 to 2012. This led to 198 observations for 22 roundabouts, representing a panel dataset with 9 observations per roundabout.

Table 1 presents the descriptive statistics of the explanatory variables included in the model. The explanatory variables are broadly categorized into three main categories including exposure variables, roadway geometric and traffic variables, and spatial or land-use characteristics.

TABLE 1 Summary Statistics of Variables Included in the Model

Exposure Variables				
Continuous variables	**Mean**	**Std. Dev.**	**Min.**	**Max.**
AADT along major Road	21493.51	5069.91	10965	36874
AADT along minor Road	10773.15	3629.83	863	18219
Average Daily Pedestrian crossing volume (ADPCV)	19420.27	13810.69	4616	54912
Average Daily male Pedestrian crossing volume	12160	9386.53	1645	38576
Average Daily female Pedestrian crossing volume	7286.30	5061.14	2043	22315
Roadway and Traffic Variables				
Continuous variables	**Mean**	**Std. Dev.**	**Min.**	**Max.**
Maximum gradient of major approach road (%)	4.55	2.39	0.8	8.32
Diameter of the central island (m)	37.59	16.35	17.30	78.30
Number of circulating lanes in the roundabout	2.5	0.66	2	4
Number of lanes along major road	6.73	0.97	6	8
Number of lanes along minor road	2.73	1.42	2	6
Indicator variables	**Count[1]**	**% Total**		
Presence truck apron =1, otherwise =0	45	22.7		
Roundabout configuration (four legs=1, otherwise three legs=0	126	63.6		
Posted speed limit along major road (if posted speed limit ≥80Km/h = 1, otherwise = 0)	81	40.9		
Availability of bus stop within 20 meters of major approach road	108	54.6		
Presence Jersey (Concrete) median barriers along major road	72	36.4		
Presence of raised medians on the major approach road	99	50.0		
Availability of fence on sidewalk of major road = 1, otherwise =0	81	40.9		
Availability of sidewalk on Minor road =1, otherwise=0	99	50.0		
Spatial Characteristics				
Indicator variables	**Count[1]**	**% Total**		
Presence of a public transport terminal beside the roundabout = 1, otherwise = 0	36	18.2		
Presence of Schools within 100 meters radius of the roundabout = 1, otherwise =0	54	27.3		
Availability of an alcohol bar within 300 meters radius of the roundabout = 1, otherwise = 0	72	36.4		
If the roundabout is located at office and commercial areas = 1, otherwise = 0	81	40.9		

[1]Count of 1 in each category

Exposure variables included annual average daily traffic (AADT) along major and minor roads, average daily pedestrian crossing volume at the roundabout, average daily male pedestrian crossing volume, and average daily female pedestrian crossing volume. The Ethiopian road authority usually conducts weekly traffic counting three times (June-

September, October-January and February-May) in a year to represent counts for different seasons. These weekly counts were then converted to AADT. The AADT along major and minor roads in this study were supplied by the Ethiopian road authority[32]. The pedestrian crossing volume was however collected manually. To estimate average pedestrian crossing volumes at roundabouts, the counting was scheduled for each four-month season. The counting within each season was conducted on one representative weekday for 12 hours (7:00 AM to 7:00 PM) and on one representative weekend for two hours. The number of pedestrians crossing major and minor roads (within 50m) as well as through the roundabouts was combined to estimate the total number of pedestrians crossing a roundabout. Weekday and weekend counts were then computed from seasonal factors in the annual traffic count report of the Ethiopian Road Authority to estimate average pedestrian crossing volumes of roundabouts during each four-month period. Gender was also captured during the pedestrian crossing volume counts and hence the average pedestrian crossing volume of males and females were used as explanatory variables in the model.

Roadway geometric and traffic variables along major and minor roads included number of lanes, roundabout configuration (four-legged or three-legged), posted speed limit, maximum gradient of the approach, presence of a concrete barrier as a divider, presence of raised medians, presence of a sidewalk, presence of a fence along the sidewalk and presence of a bus stop within 50m of the yield line on an approach road. In addition, several variables related to the central island of the roundabout included number of circulating lanes, diameter of the central island, and presence of a truck apron around the central island. The truck apron refers to the low profile concrete apron around the central island that accommodates the overhanging portion of a truck or large vehicle while they are circulating around the island. A schematic diagram of a typical modern roundabout in Addis Ababa is shown in Figure 1.

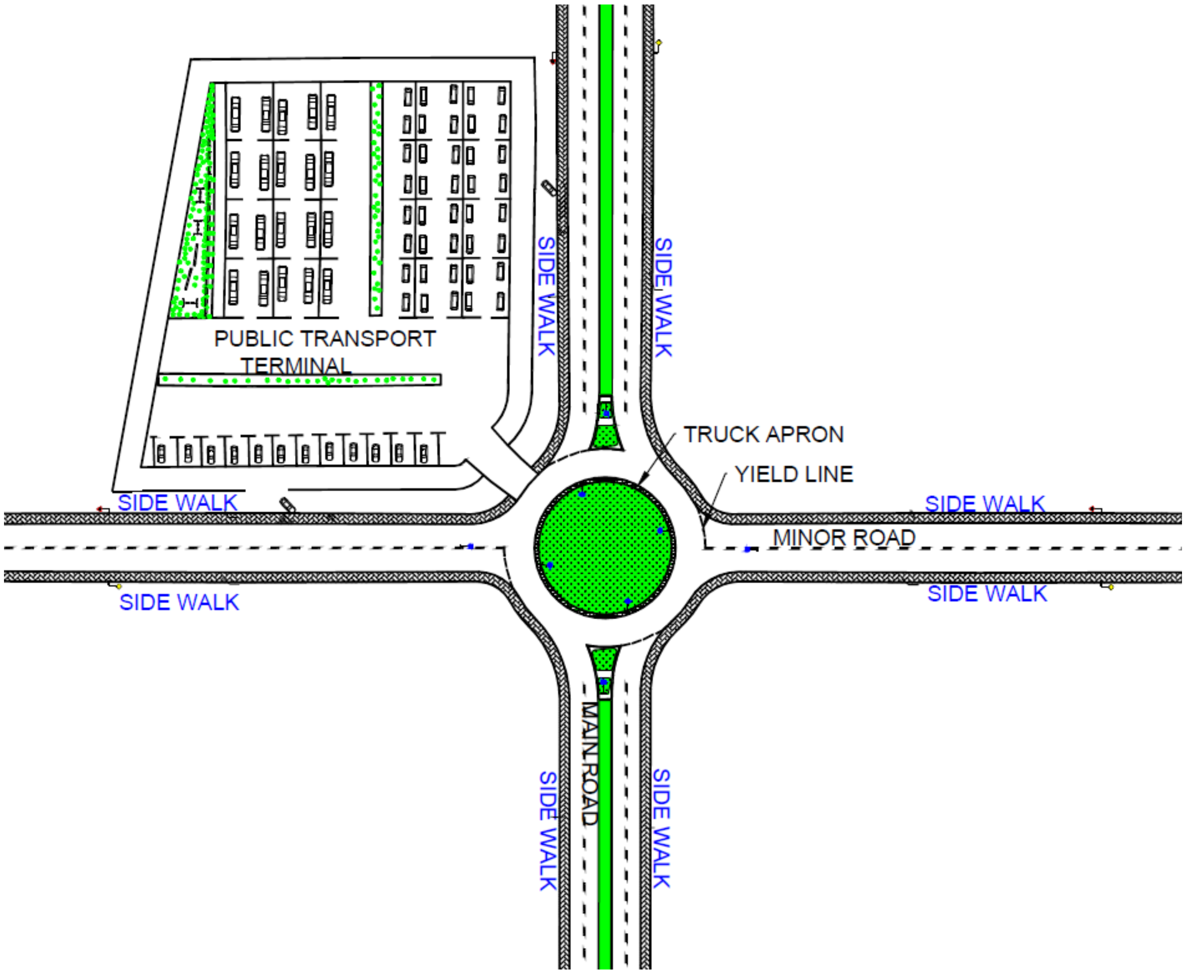

FIGURE 1 Typical modern roundabout in Addis Ababa

Spatial variables included presence of a school zone within 100m of the roundabout, availability of alcohol-serving bars within a 300m radius of the roundabout, whether the roundabout was located in office and commercial areas, and the presence of a public transport terminal beside the roundabout. The provision of a public transport terminal beside a roundabout in Addis Ababa is shown in the schematic drawing of a roundabout in Figure 1.

RESULTS

Table 2 shows the parameter estimates of both the REP and RENB models of pedestrian crashes at modern roundabouts. Goodness-of-fit statistics of these models are also reported in Table 2. The variance of the location-specific random effect, $\exp(\delta_i)$ of the REP model is significant at a 5% significance level. Similarly, distributional parameters a and b of the random effect of the RENB model are statistically significant. These findings indicate that a strong structural temporal correlation effect exists among pedestrian crash counts at roundabouts, and justifies the added complexity of the random effect model. In other words, these noted effects imply that the intercepts are different across roundabouts but the effects of explanatory variables on pedestrian crashes at modern roundabouts are fixed and similar. Akaike's Information Criterion (AIC) and Bayesian Information Criterion (BIC) estimates for the REP model are 502.5 and 528.8 respectively, while the corresponding estimates for the RENB model are 507.8 and 533.8. The REP model of pedestrian crashes at modern roundabouts appears to provide a marginally superior fit with lower AIC and BIC values, thus the REP model results are discussed in the remainder of the paper.

The best-fitting REP model contains six significant predictors of pedestrian crashes at modern roundabouts, including (1) the product of traffic flows along major and minor roads, (2) average daily pedestrian crossing volume, (3) maximum gradient of the major approach road, (4) presence of raised medians along major road, (5) presence of a public transport terminal beside roundabout, and (6) presence of schools within a 100m radius of the roundabout. All parameters have plausible signs and magnitudes.

The logarithm of the *product of AADT along major and minor road* was significant (*95% CI: 0.06, 1.58; IRR=2.26*) in predicting pedestrian crashes at modern roundabouts. The *IRR* value indicates that pedestrian injury crashes increase by 2.26 times if the logarithm of the product of AADT along major and minor roads increases by one unit, all else being equal. So for example, if traffic increase from 5000 and 1000 vehicles per day on major and minor roads respectively to 10,000 and 1350, crashes would increase by a factor of 2.26. Traffic flows on the major and minor roads capture exposure to risk, and the non-linear relation is captured through the log transform. Prior research [e.g., 33, 34]has also revealed non-linear relationships between pedestrian crashes and traffic volumes.

The logarithm of the *average daily pedestrian crossing volume* is positively associated (*95% CI: 0.03, 1.28; IRR=1.92*) with pedestrian injury crashes. A unit increase in the logarithm of average daily pedestrian crossing volume is associated with about a 92% increase in pedestrian injury crashes. The logarithmic transformation of the crossing volume indicates a non-linear relationship between pedestrian crashes and crossing volumes at roundabouts. Exposure to crash risk is directly related to the pedestrian crossing volume and hence pedestrian crashes are likely to increase with higher crossing volumes. Pedestrian volumes have also been significant predictors of pedestrian crash risk in other studies[e.g., 35].

TABLE 2 Safety Performance Functions of Pedestrians Crashes at Modern Roundabouts

Variables	Random Effect Poisson Model						Random Effect Negative Binomial Model					
	Estimate	**IRR**	**SE**	**z-statistic**	**p-value**	**95% CI**	**Estimate**	**IRR**	**SE**	**z-statistic**	**p-value**	**95% CI**
Constant	-9.71		3.23	-3.01	0.00	[-16.04, -3.39]	4.97		327.65	0.02	0.99	[-637.21,647.15]
Log of the product of major and minor road AADT	0.82	2.26	0.39	2.10	0.04	[0.06, 1.58]	0.99	2.70	0.40	2.46	0.01	[0.20,1.78]
Log of average daily pedestrian crossing volume	0.65	1.92	0.32	2.05	0.04	[0.03, 1.28]	0.68	1.97	0.34	1.99	0.05	[0.01,1.35]
Maximum gradient of major approach road	0.11	1.12	0.04	2.95	0.00	[0.04, 0.19]	0.10	1.10	0.04	2.39	0.02	[0.02,0.18]
Presence of raised medians on the major approach road	-0.41	0.66	0.18	-2.29	0.02	[-0.77, -0.06]						
Presence of a public transport terminal beside the roundabout	0.50	1.65	0.2	2.53	0.01	[0.11, 0.89]	0.60	1.82	0.22	2.77	0.01	[0.18,1.02]
Presence of Schools within 100 meters radius of the roundabout	-0.38	0.68	0.20	-1.87	0.06	[-0.78, 0.02]	-0.47	0.62	0.22	-2.20	0.03	[-0.89,-0.05]
Total number of observations	198						198					
Log-likelihood at convergence	-243.25						-245.74					
Log-likelihood at zero	-255.74						-306.30					
Variance of the location-specific effect	0.06		0.04			[0.01, 0.26]						
Parameter a							1.52e+08		4.99e+10			[2.0e-271,1.2e+287]
Parameter b							11.80		7.83			[3.21,43.32]
degrees of freedom (*df*)	8						8					
AIC	502.50						507.48					
BIC	528.81						533.79					

Maximum gradient of the major approach road is one of the significant (*95% CI: 0.04, 0.19; IRR=1.12*) predictors positively associated with pedestrian crashes at roundabouts. A 1% increase of the gradient of the major approach is associated with a 12% increase in pedestrian injury crashes. There are four possible reasons to explain increased pedestrian crashes with steeper gradients. First, steep gradients along roundabout approach roads serve to restrict sight distances of both drivers and pedestrians. Second, speed is likely to be higher for vehicles travelling on approaches with negative gradients. Moreover in Addis Ababa drivers may not exercise proper care in controlling their speeds on negative approach gradients, since speed regulation and enforcement are limited. Third, vehicle performance is crucial while traversing an approach road with a steep gradient. Akloweg et al. (2011) reported that 65% of vehicles in Ethiopia are more than 15 years old, and older vehicles are at greater risk of mechanical malfunction and degraded braking performance, with obvious increased potential crash risk for pedestrians. Fourth, Ethiopian roads generally do not conform to international standards, such as the Highway Capacity Manual [2]. A substandard roadway and/or intersection design particularly along a negative gradient approach to a roundabout might also contribute to deterioration in pedestrian safety.

The *presence of raised medians along the major approach road* is negatively associated (*95% CI: -0.77, -0.06; IRR=0.66*) with pedestrian crashes at roundabouts. The corresponding reduction of pedestrian crashes is 44% compared to roads without raised medians. Several prior studies have reported that raised medians significantly reduce pedestrian crashes (e.g., Schneider et al., 2010; Zegeer et al., 2005) [36, 37]and assist pedestrians to cross roads safely [38]. Apart from separating opposing traffic, raised medians provide pedestrians a refuge while crossing a road, so they can effectively plan to cross one direction of traffic at a time.

The *presence of a public transport terminal* in close proximity to a roundabout is positively associated (*95% CI: 0.11, 0.89; IRR=1.65*) with pedestrian crashes at roundabouts. The *IRR* suggests that close proximity of a public transport terminal increases pedestrian crashes as much as 65% compared to those without a public transport terminal. Pedestrian movements are of course generally higher around public transport terminals, resulting in increased pedestrian crash risk over and above the risk captured by vehicle and pedestrian exposure. It is anticipated that this effect captures merging and weaving conflicts of vehicles and pedestrians in an intense location near the roundabout that is not captured by other exposure metrics. Indeed, Haque and Washington [25]have reported that complex traffic movements due to multiple access points close to an intersection are positively associated with intersection crashes.

The *presence of schools within a 100m radius of a roundabout* is negatively associated (*95% CI: -0.78, 0.02; IRR=0.66*) with pedestrian crashes at roundabouts, although significance was around 10%. A roundabout near a school is associated with 32% fewer pedestrian crashes. In contrast, earlier research [e.g., 39, 40] suggests that pedestrian crashes, particularly crashes involving school children, are higher in areas near to schools. The opposite finding of this study may be attributable to the developing country context, where roads around schools are often congested due to illegal stopping of vehicles and associated reduced speed of traffic. This finding requires further investigation of traffic operations and safety near to schools in developing countries.

DISCUSSION AND CONCLUSIONS

This paper develops safety performance functions for pedestrian injury crashes at modern roundabouts in Addis Ababa, Ethiopia to explore the potential effects of significant geometric, traffic and spatial factors. In addition to common geometric and traffic features of roundabouts, extensive and unique spatial data were collected from 22 modern roundabouts in Addis Ababa, representing 56% of such roundabouts within this city. Treating the data as time-series cross-section panels, this study estimated two plausible random effect models and found the random effect Poisson (REP) to be marginally superior to the random effect negative binomial (RENB) model in explaining pedestrian injury crashes at modern roundabouts.

The REP model identified a number of key variables related to pedestrian safety at modern roundabouts in Addis Ababa, including pedestrian crossing volumes, traffic flows, the presence of raised medians, gradients of approach roads, presence of public transport terminals beside a roundabout, and the presence of nearby schools. The findings will be helpful for identifying high risk sites when the models are used as safety performance functions, and for exploring possible remedial measures when variables are interpreted as contributing factors explaining crash occurrence.

The model identified two exposure variables as influential on crash counts, including traffic flows and pedestrian crossing volumes. Like many other cities in developing countries, walking is one of the primary modes of transport in Addis Ababa. The current land use and road environment facilities do not ensure proper crossing facilities for pedestrians at roundabouts. As a result, pedestrians cross roads in relatively unpredictable ways compared to more regulated westernized transport systems. At high pedestrian activity roundabouts, designing proper crossing infrastructure to separate pedestrians from motorized vehicles should be given priority.

The gradient of the major approach road to a roundabout negatively affects pedestrian safety. A roundabout approach road should be properly designed so that gradients do not compromise stopping sight distance, which is important to ensure safety of pedestrians and other road users. In addition to considering sight distance in roundabout design, authorities should review how roundabout design considerations influence approach speeds—a common consideration in roundabout design in the UK and Australia—especially for high speed approaches.

The presence of raised medians along the major approach to roundabouts is associated with reduced pedestrian crashes. Raised medians provide refuge for crossing pedestrians so that one need only consider crossing one direction of traffic at a time. Roundabouts lacking medians and with high pedestrian exposure and crash risk might be retrofit with raised medians. The findings also suggest that the provision of appropriate crossing facilities is vital for pedestrian safety at roundabouts. Pedestrian crossing facilities are often not given proper attention in Addis Ababa. Installation of appropriate crossing facilities coupled with raised medians along the approach road would definitely improve safety of pedestrians at the roundabout.

Pedestrian crashes were higher at roundabouts near public transport terminals, where the spatial intensity of pedestrian-vehicle conflicts is high. The entry and exit of pedestrians and vehicles from public transport terminals should be carefully considered and separated at these locations. Based on the findings of this study, some possible improvements of the existing roundabouts in Addis Ababa are depicted in Figure 2.As contrastedin Figure 1 and Figure 2, the entry and exit to a public transport terminal could be relocated to downstream of a roundabout to reduce both vehicle-pedestrian and vehicle-vehicle conflicts around the circulating traffic. There should be appropriate provision of pedestrian crossing facilities at a roundabout, and they could be positioned next to access points of the public transport terminal. Sidewalks along approaches of a roundabout could be equipped with pedestrian fences to reduce haphazard movements of pedestrians near the central island, and thereby reducing the pedestrian exposure to crash risk around high conflicting locations. In addition, there should be a provision of raised medians along major approaches of a modern roundabout.

Few studies [e.g., 41, 42] in western countries have reported a positive association between pedestrian crashes and proximity of bus stops to intersections. When testing for a possible effect in Addis Ababa, however, the presence of bus stop within 20 meters along the major approach was not found to be significant. Similarly, the presence of bars serving alcohol within a 300 meters radius of a roundabout was not significant, despite several western studies [e.g., 41, 43] having reported these effects. Why these effects were not significant in Addis Ababa might be explained by a number of factors, and highlight contextual differences between developed and developing nations. These differences further support the notion that safety performance functions of transport facilities like modern roundabouts should be developed in the developing nation setting.

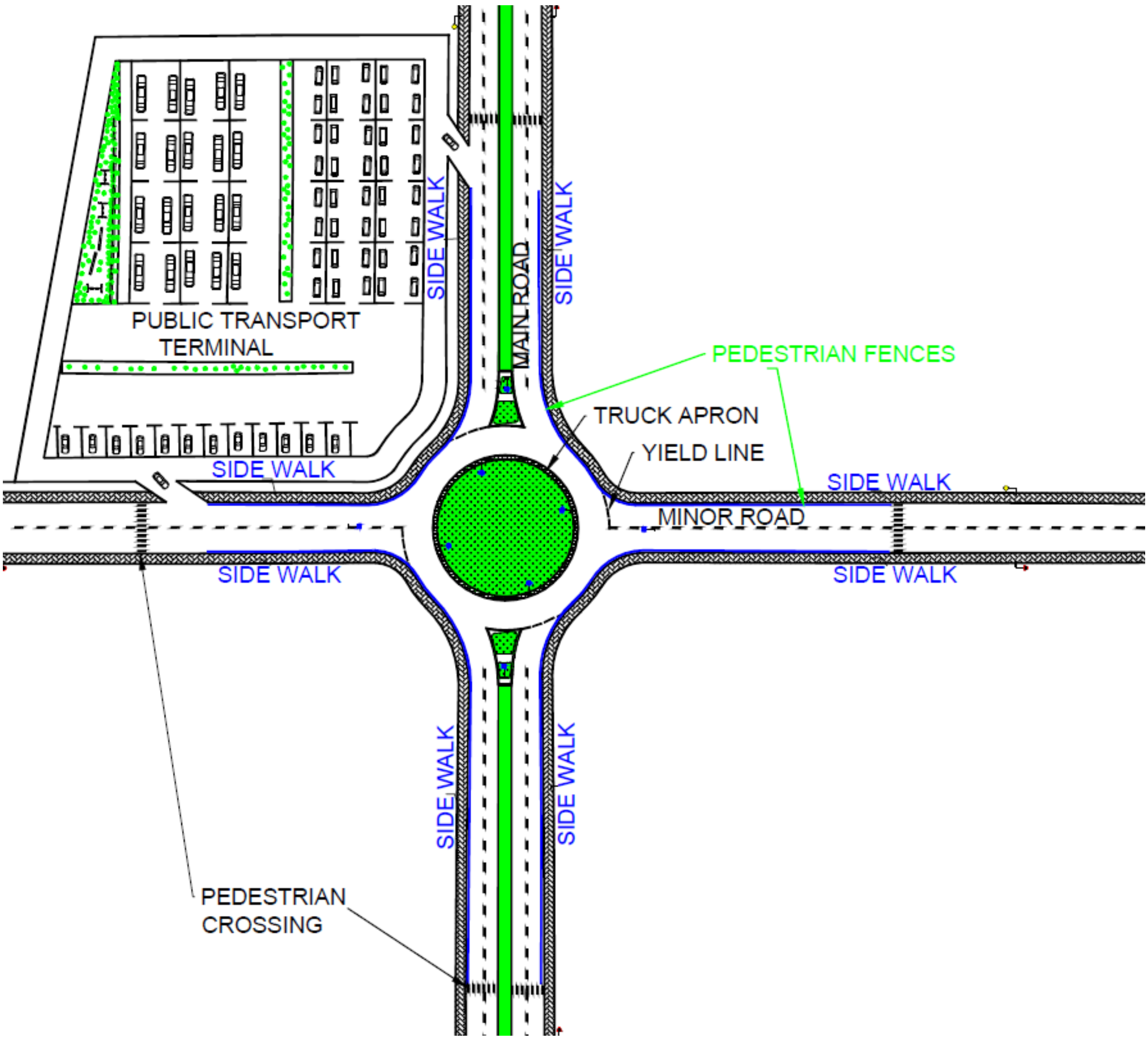

FIGURE 2 Suggested improvements of the existing modern roundabouts

Overall, the findings of this study have revealed new insights into pedestrian safety at modern roundabouts in a developing country. These findings are intended to assist transport planners, road designers, and road safety professionals in the future consideration of pedestrian safety in the developing country context. The safety performance function developed may also assist in the identification of accident black spots—a routine safety management practice. The installation of modern roundabouts is a recent initiative in Ethiopia, and authorities should carefully consider the range of pedestrian safety implications highlighted in this paper.

Few studies have developed crash prediction models for pedestrians in developing countries. This is the first known study to develop safety performance functions for pedestrians at modern roundabouts in a developing country context. One of the major challenges confronting researchers in developing countries is the availability of complete and reliable data. Extensive efforts have been expended in this study to collect various roadway geometry, traffic and spatial variables to support development of safety performance functions of pedestrian crashes at modern roundabouts in Addis Ababa, Ethiopia. Manual data collection of pedestrian volumes might be subject to some errors; however, this was the best available option to the authors for collecting data in Addis Ababa.

Factors affecting pedestrian safety at roundabouts may of course differ from one developing country to another. The developed safety performance function might guide other researchers attempting to develop pedestrian crash prediction models. A possible extension to this study is the development of simultaneous equation models so factors affecting different types of crashes at modern roundabouts could be identified, leading to more targeted countermeasures with focus on crash severity rather than crash frequency, as was the focus in this study.

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