Cyclists casualty severity at roundabouts – To what extent do geometric characteristics of roundabouts play a part

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Abstract

Introduction: In general, priority junctions are converted into roundabouts to increase capacity and reduce vehicle accidents. However, previous research has indicated that roundabouts are dangerous for vulnerable road users, especially cyclists. ***Method:*** This paper investigates which design parameters influence cyclist casualty severity at give-way (i.e. non-signalized) roundabouts with mixed traffic, using the UK Department for Transport's STATS19 accident database. First, a correlation matrix was generated to observe the relationship between variables. Second, dimension reduction was applied to geometric design parameters in order to reduce the number of variables and generate underlying factors which were subsequently used as independent variables in a logistic regression analysis. Finally, a Binary Logistic Regression Model (BLRM), with serious and slight casualties as dependent variables, was applied in three steps. BLRM1 included speed limit, sociodemographic characteristics and meteorological conditions. BLRM2 consisted of geometric design variables. BLRM3 included the factors that were generated by the dimension reduction. ***Results:*** The correlation matrix revealed that the number of lanes on approach and half width on approach were statistically significantly correlated at the 99% confidence level, while certain variables relating to geometric design (i.e. entry path radius, number of arms, number of flare lanes on approach, type of roundabout and number of circulating lanes), sociodemographic characteristics (i.e. gender and age of cyclist), speed limit and meteorological related variables (i.e. daylight, weather and road surface condition) were not statistically significant at the 95% confidence level. Two main factors were identified, namely *Approach Capacity* (Factor 1) and *Size of Roundabout* (Factor 2). The BLRMs showed that a unit increase in speed limit reduces the safety of cyclists by 2% (odds ratio 1.02) at roundabouts. The probability of a serious casualty increases by approximately five times (odds ratio 4.97) for each additional lane on approach and by 4% (odds ratio 1.04) with a unit increase in entry path radius. Also, a unit increase in *Approach Capacity* was found to increase the severity of cyclist casualties by 86% (odds ratio 1.86) at roundabouts. ***Practical applications*:** While this research studied roundabouts in Great Britain, the methodological approach and statistical techniques are applicable to other countries and the findings are likely to be of value to decision makers worldwide.

Keywords:

Cyclist Safety; Approach capacity; Casualty severity; Principle component analysis; Binary logistic regression

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1. Introduction

Transport authorities and policy makers continue to encourage people to use sustainable travel modes. However, personal safety can be considered as one of the main barriers associated with the use of sustainable travel modes in general, and walking and cycling in particular. As sustainable travel is encouraged for various reasons (e.g. reduced traffic congestion, and health and environmental benefits), the safety of vulnerable road users must be addressed urgently (ETSC, 2018). It is assumed that an improved transport system should not only focus on travel time savings, but also aspire to enhance the safety and comfort of travellers (Litman & Burwell, 2006). The European Commission's 2020 target emphasizes that road safety is a major issue for vulnerable road users, especially cyclists (European Commission, 2010).

Infrastructure design plays a major role in creating a safer travel environment for road users. Roundabouts are designed to improve traffic safety by decreasing the number of conflict points compared to signalized junctions (Montella, 2011). Designs usually aim to reduce casualties to make roundabouts safer for all road users; however, it is questionable that cyclists benefit from safety improvements to the same extent as motorized vehicle users (Daniels, Nuyts, & Wets, 2008; De Brabander & Vereeck, 2007; Elvik, 2003). Since non-motorized users, including cyclists, are considered vulnerable from the point of view of road safety, they are at a higher risk of serious injury compared to motorized users (Dissanayake, Aryaija, & Wedagama, 2009). Local and national governments in Europe continue to encourage cycling (European Commission, 2010), therefore more emphasis on infrastructure design to create safer environments for cyclists is needed in the future. While better cyclist infrastructure has a positive impact on cyclist safety (Tolley, 2003), it is still not clear what type of road infrastructure at roundabouts improves cyclist safety.

This paper aims to generate a fundamental understanding of how geometric design parameters as well as sociodemographic characteristics, speed limit and meteorological variables affect cyclist casualty severity. First, a review of those variables that have been found to affect cyclist safety will be presented along with a critique of modelling techniques used in previous studies. After detailing the aim and analytical steps, the data collected for this study will be described. The analysis methods and results of the statistical modelling are then discussed before conclusions are drawn.

2. Variables affecting cyclist safety at roundabouts

Converting intersections to roundabouts increases the probability of cyclist casualty occurrence (Daniels et al., 2008; Daniels, Brijs, Nuyts, & Wets, 2011). Furthermore, fatal and serious cyclist casualties were more likely to occur at roundabouts (Daniels, Brijs, Nuyts, & Wets, 2009; De Brabander & Vereeck, 2007; Polders, Daniels, Casters, & Brijs, 2014). Daniels et al. (2008) stated that there was a 41–46% increase in fatal and serious cyclist injuries at roundabouts. Given this increase, there is a clear need to understand the reasons why cyclist casualties increase at roundabouts in general, and also why they increase in severity level when a roundabout is put in place.

A road crash is a complex event influenced by multiple variables such as drivers' physical and mental condition, the geometric design of the road, traffic characteristics, the weather and travel motivation (Aljanahi, Rhodes, & Metcalfe, 1999). Therefore, considerable attention has been given to these variables when evaluating cyclists' safety at roundabouts, particularly in Northern European countries (Daniels et al., 2008, 2009, 2011; Daniels, Brijs, Nuyts, & Wets, 2010; De Brabander & Vereeck, 2007; Hels & Orozova-Bekkevold, 2007; Jensen, 2017; Lawton, Webb, Wall, & Davies, 2003; Møller & Hels, 2008; Polders et al., 2014).

Daniels et al. (2008) observed a 48% rise in cyclist casualties in general and a 77% rise in fatal and serious cyclist casualties in particular inside built-up areas after junctions were redesigned as roundabouts. However, no significant change in cyclist casualties was observed outside built-up areas. Accordingly, it can be concluded that roundabouts may not always be the most appropriate solution for cyclists, especially in urban locations. Earlier research showed that signalized junctions were performing better than roundabouts with regards to cyclist casualties (De Brabander & Vereeck, 2007). However, Jensen (2017) found that in high speed limit locations, converting intersections to single lane roundabouts decreased the number of crashes and severity of cyclist casualties. De Brabander and Vereeck (2007) demonstrated that cyclists have a preference for low speed zones. Hels and Orozova-Bekkevold (2007) showed that the probability of an accident occurring and cyclist volume were statistically significantly correlated. These results from Daniels et al. (2008), De Brabander & Vereeck (2007), Jensen (2017) and Hels and Orozova-Bekkevold (2007) when considered together suggest that speed is an underlying variable affecting cyclist casualties and steps taken through junction design that seeks to reduce speed are safer.

Since the speed and flow of traffic streams, ideally, match roundabout design features (DfT, 2007), previous research has focused on geometric design parameters. An earlier study by Lawton et al. (2003) stated that, in order to increase cyclists' safety, roundabout geometry should be made tighter at the approach, entry and circulating locations by enlarging the central island and reducing the number of lanes on approach and circulatory carriageways. However, analysing the impact of geometric design features on cyclist casualty severity was not attempted by Lawton et al. (2003) due to limited records. Hels and Orozova-Bekkevold (2007) assessed the impact of geometric design features on cyclist casualty occurrence by investigating the 'drive curve' (entry path radius). They realized that the drive curve is directly related to vehicle speed and consequently considered the drive curve as a translation of vehicle speed when the analysing the yearly rate of cyclist casualties. Hels and Orozova-Bekkevold (2007) concluded that a higher drive curve (entry path radius) increases the probability of a cyclist accident. Entry path is the most important geometric design parameter for safety at roundabouts since it is a proxy of speed of the vehicle (DfT, 2007). In addition, roundabout age, the drive curve and the apron width of roundabouts appeared to have a statistically significant impact on cyclist casualty occurrence (Hels & Orozova-Bekkevold, 2007). Jensen (2017) conducted a comprehensive study on the impact of single lane roundabouts with different sizes of central islands on cyclist safety. The study concluded that single lane roundabouts with a 20–40m central island were safer than those having a larger or smaller central island radius. In addition, Jensen (2017) stated that single lane roundabouts with a >2m elevated central island increased safety for cyclists. The UK Reid and Adams (2010) highlighted that all road infrastructure related variables, such as the number of flare lanes on approach, half width on approach, entry path radius, number of arms, central radius, entry width, number of lanes on approach and type of roundabout are fundamental parameters in the decision-making process of how to reduce cyclist casualties. However, the report stressed that there is insufficient evidence to understand the relationship between cyclist safety and road infrastructure parameters, highlighting again the considerable gap in research that had already been suggested by previous studies (Daniels et al., 2008, 2011; Polders et al., 2014).

Daniels et al. (2010) stated that an older age for all types of road users increases casualty severity at roundabouts; however, the impact of gender is uncertain. In addition, Daniels et al. (2010) found that the severity of casualties at roundabouts increased at night and outside built-up areas regardless of the types of road user involved. Due to the limited research in this field, it was suggested that future studies should consider extending knowledge of risk parameters using information from different countries (Daniels et al., 2009, 2011).

Clearly, overall, there are a number of variables that influence the risk of cyclist casualties occurring, and future studies should consider all parameters: network and cyclist casualties and geometric design. The research presented in this paper attempts to address the identified research gaps by developing a comprehensive model that includes geometric design parameters, sociodemographic characteristics, speed limit and meteorological variables, to understand which variables statistically significantly influence cyclist casualty severity at roundabouts.

3. Modelling techniques for road casualty analysis

Various methods have been used to analyse cyclist accident data including multiple linear regression (Daniels et al., 2009; Møller & Hels, 2008), logistic regression (Daniels et al., 2010; Hels & OrozovaBekkevold, 2007) and Empirical Bayes (Daniels et al., 2009). When determining the prediction probabilities of the occurrence of a specific accident type based on survey data, the Empirical Bayes method is commonly used in safety research (Hauer, Council, Harwood, & Griffith, 2009). A classic multiple linear regression has the dependent variable y and a set of exploratory independent variables x_1, x_2, $x_3, \dots$ x_n (Fahrmeir, Kneib, Lang, & Marx, 2013). Linear regression is suitable when the dependent variable is continuous. When the dependent variable has a limited number of possible values, categorical or continuous, a Binary Logistic Regression Model (BLRM) is more appropriate (Osborne, 2008) and has been used frequently in road casualty modelling (Daniels et al., 2010). The outcome of the model should be binary or dichotomous (Hosmer & Lemeshow, 2000) and the parameter estimates give the magnitude and sign (i.e. negative or positive) to suggest how the independent variables relate to the dependent variable. The rate of increase or decrease in the probability of the outcome is determined by calculating the odds ratios when the value of the independent variables increases by a multiplier for a one unit change in the dependent variable (Daniels et al., 2010). The study reported in this paper investigates the variables that influence cyclist casualty severity at roundabouts, rather than calculating the probabilities of casualty occurrences. Furthermore, the dependent variable for this paper was cyclist casualty severity. Given that the dependent variable is categorical, with the two outcomes of either slight or serious, BLRM was considered as the most appropriate analytical application.

According to Peduzzi et al. (1996), there are three types of error that occur in Binary Logistic Regression: overfitting, under fitting and paradoxical fitting. Therefore, the number of independent variables included in the model needs to be determined carefully. Previous research (Peduzzi et al., 1996) recommends that the minimum 10 events per variable (EPV) approach is acceptable in BLRM. Agresti (2007) identified that adding too many variables leads to poor standard errors. This research adopted the advice of Peduzzi et al. (1996) and used the minimum of 10 EPV. When the number of observations is not higher than the recommended limit (Peduzzi et al., 1996), the variables can be applied individually in the regression model (Hels & Orozova-Bekkevold, 2007).

Suhr (2005) stated that a strong correlation between variables leads to errors in a regression model and the author recommended that three criteria should be applied in order to obtain reliable results. These are: selected variables should not be included in the model; composite scores should be created based on measured variables in order to explain less variance; and dimension reduction should be carried out to reduce the number of variables that explain more variance. Suhr (2005) stated that the best way to obtain better regression is dimension reduction with fewer variables explaining more variance.

Dimension reduction is a statistical technique for simplifying complex sets of data (Kline, 1994). There are several methods that can be applied to achieve dimension reduction including principle components, unweighted least squares, generalized least squares, maximum likelihood and factoring techniques including principal, alpha and image. The most commonly used method is Principal Component Analysis, or PCA (Jolliffe, 2002), which was used in this study. In PCA, variables are grouped into factors with a loading level. The loadings of the variables within factors are given in a rotation matrix. The aim of the rotation is to obtain the least number of factors while increasing the weights of the variables. Rotations of the axes are divided into two groups: orthogonal rotation (90^0 rotated) and oblique rotation (not rotated through 90^0; Rummel, 1988). If the outcome of component correlation matrix is between -0.32 and +0.32 (low correlation), orthogonal rotation should be preferred. Otherwise, when the result is outside of this interval (high correlation), oblique rotation should be applied (Tabachnick, Fidell, & Osterlind, 2014).

Reliability is an essential element in the interpretation of a measured variable (Tavakol & Dennick, 2011). Reliability tests can be carried out using Cronbach's Alpha (α) value, which gives the internal consistency between variables (Yurdugül, 2008). If the Cronbach's Alpha value is equal to or greater than 0.70, there is a statistical acceptable reliability between variables (Tavakol & Dennick, 2011). Furthermore, Yurdugül (2008) reported that the minimum number of samples for measuring the alpha could be determined based on the eigenvalue obtained from PCA. Yurdugül (2008) suggested that the minimum required number of samples should be 100, when the first eigenvalue was between the values of three and six.

4. Aim and analytical steps

The overall aim of this study is to gain a fundamental understanding of how geometric design parameters, sociodemographic characteristics, speed limit and meteorological variables impact upon the severity of cyclist casualties at roundabouts.

First, the correlation matrix was generated to observe the relationship between independent variables. Second, dimension reduction was applied to the geometric design variables in order to generate the factors. Finally, a BLRM with serious and slight casualties as the dependent variable was applied in three ways.

BLRM1 included speed limit, sociodemographic and meteorological conditions; BLRM2 consisted of geometric design variables; and BLRM3 considered the factors generated by dimension reduction.

5. Data collection

Given the availability of data for roundabout geometry, this research considered the North East of England in the UK as the case study area (see Fig. 1a and b). The GB STATS19 records of cyclist casualties at give way (non-signalized) roundabouts were obtained from the Traffic and Accident Data Unit (TADU) using Capita Innovations' Road Traffic Accident System held by Gateshead Council located in the North East of England. For this study, accident data between 2011 and 2016 (inclusive) have been collected and analysed in regard to meet the road safety strategy announced by the European Road Safety Policy Orientation for 2011–2020 (European Commission, 2010). The cyclist casualty data includes: date and time of occurrence, location (geographical coordinates), a general description of the accident, daylight, weather, road surface conditions and sociodemographic information such as age and gender of the cyclist.

Casualty severity is reported in the data in three categories (i.e. fatal, serious and slight). If death occurs within 30 days of the collision, then the casualty is categorized as fatal. 'Serious' injuries include, for example, a broken neck or back, a severe head injury, severe chest injury, loss of (or part of) an arm or leg, deep penetrating wounds or severe general shock requiring treatment in hospital or being detained in hospital. Severe casualties also include those who die 30 or more days after the collision from their injuries. 'Slight' injuries include neck pain, shallow cuts, sprains and strains, bruising and slight shock that may or may not require medical treatment.

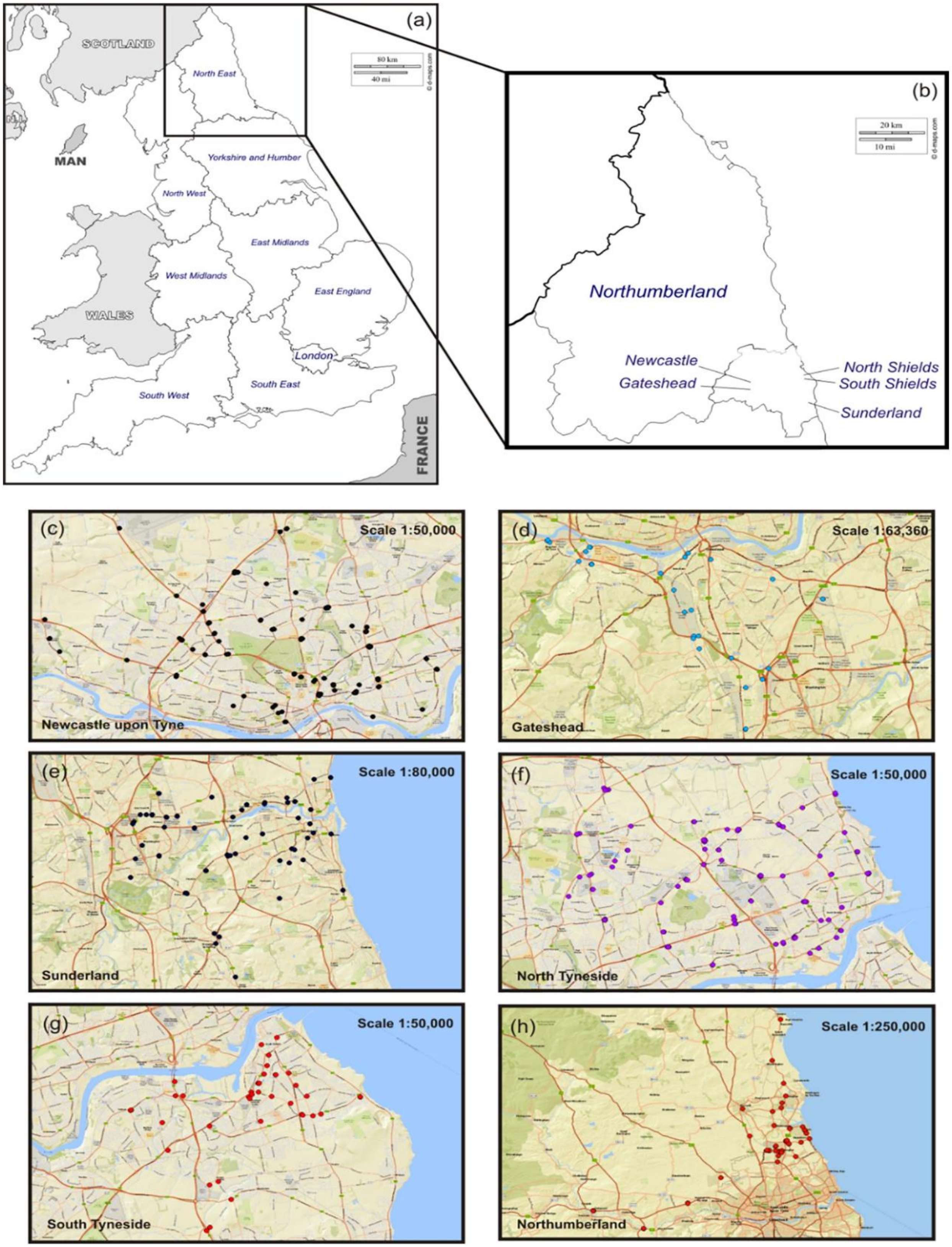

Fig. 1. Visualization of casualty locations (map a: edited from http://d-maps.com/m/europa/uk/angleterre/angleterre21) (map b: edited from http://d-maps.com/m/europa/uk/englandne/englandne12) (map c, d, e, f, g and h: generated in ArcMap).

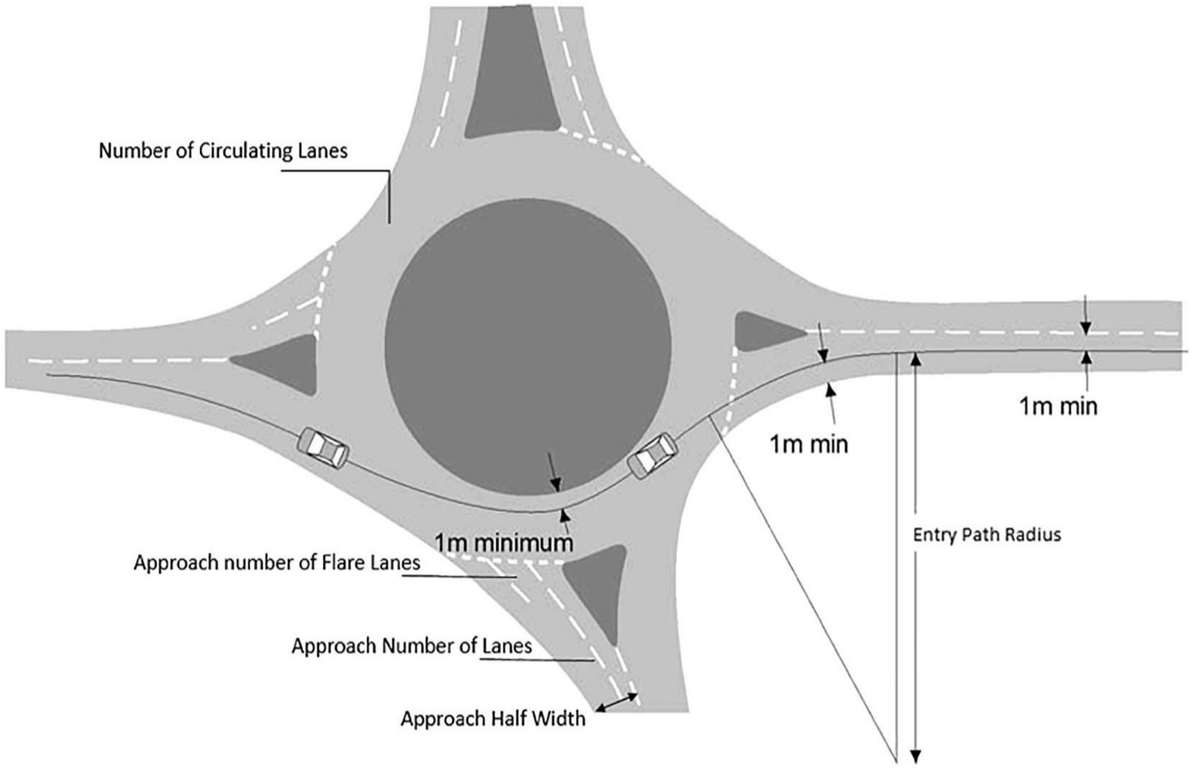

Fig. 2. Geometric design parameters on a roundabout (generated from the Design Manual for Roads and Bridges, 2007).

During the study period 2011–2016, 439 cyclist casualties were recorded at 209 roundabouts (of which 69 were serious and 370 were slight casualties) in six areas in North East of England, namely Newcastle upon Tyne, Gateshead, Sunderland, North Tyneside, South Tyneside and Northumberland (see Fig. 1c, d, e, f, g, h). There were no fatal cyclist casualties recorded at the selected roundabouts during the study period. The geometric layout of the roundabouts where casualties were recorded was downloaded from Digimap as AutoCAD files. The coordinates of the cyclist collisions were imported into the maps in order to measure the geometric variables, which included number of lanes on approach, half width on approach, entry path radius, number of arms, number of flare lanes on approach, type of roundabout and number of circulating lanes (see Fig. 2). These were measured based on the protocol outlined in the UK Design Manual for Roads and Bridges (DfT, 2007). Vehicle drivers' approach direction to the roundabout was considered when measuring the geometric design parameters. The categorical variables, severity of cyclist casualty (slight/ serious), gender (female/male) and lighting level (darkness/daylight) were recorded as binary numbers either 0 or 1. For variables with three categories, such as weather (fine/rain/other) and road surface condition (dry/wet/ice), these were coded as 0, 1, and 2 in the dataset (see Table 1).

Table 1
Cyclist casualty variable description.

Variable (abbreviation)	Descriptive Statistics
Cyclist casualty severity (Slight = 0; Serious = 1)	Slight = 370; Serious = 69
Number of lanes on approach (1; 2; 3)	1 = 306; 2 = 126; 3 = 7
Half width on approach(Metres)	Mean = 5.26; S.D. = 1.79
Entry path radius (Metres)	Mean = 66.94; S.D. = 21.38
Number of arms (3; 4; 5; 6)	3 = 72; 4 = 286; 5 = 65; 6 = 16
Number of flare lanes on approach (1; 2; 3; 4)	1 = 189; 2 = 221; 3 = 28; 4 = 1
Type of roundabout (Mini = 0; Normal = 1; Grade separated = 2)	0 = 23;1 = 354;2 = 62
Number of circulating lanes (1; 2; 3)	1 = 270;2 = 162;3 = 7
Casualty gender (Female = 0; Male = 1)	Female = 55; Male = 384
Casualty age	Mean = 39.22; S.D. = 14.17; Min. = 5; Max. = 80

Speed limit (20; 30; 40; 50; 60; 70) (mph)	20 = 5; 30 = 323; 40 = 41; 50 = 13; 60 = 42; 70 = 15
Daylight (Darkness = 0; Daylight = 1)	0 = 98;1 = 341
Weather (Fine = 0; Rain = 1; Other = 2)	0 = 373;1 = 54;2 = 12
Road surface condition (Dry = 0; Wet = 1; Ice = 2)	0 = 312;1 = 118;2 = 9

Source: Stats19 and Digimap database.

6. Data analysis

Results of each analysis step, namely generating the correlation matrix, the dimension reduction and BLRM estimation, are detailed in the following sections.

6.1. Correlation between Variables

Three groups of variables were considered in the analysis: (1) speed limit and geometric design parameters; (2) sociodemographic characteristics; and (3) meteorological variables. The appropriate correlation test was applied after investigating the structure of the data as follows: Interval: number of lanes on approach, half width on approach, entry path radius, number of arms, number of flare lanes on approach, number of circulating lanes and age of casualty; Nominal: gender, daylight, weather and road surface condition; and finally, Ordinal: type of roundabout. A normality test for the variables measured on an interval scale was carried out and it was observed that none of the variables were normally distributed. Therefore, Spearman's rho correlation was applied to group one (speed limit and geometric design parameters). In the second group, the correlation between gender and age (measured on nominal and interval scales respectively) of each casualty was undertaken using point biserial correlation because of mixed data structures. Finally, Cramer's V coefficient was calculated for group three (meteorological variables) as daylight, weather and road surface condition data were all recorded on a nominal scale.

Many of the roundabout geometric design parameters were found to be statistically significantly correlated at the 99% confidence level; however, the majority of the parameters had Spearman's rho values below 0.70, which is the minimum recommended level of correlation coefficient strength (Mukaka, 2012; see Table 2). The strong positive monotonic correlation (0.76) was calculated between number of lanes on approach and half width on approach. The correlation matrix also revealed no statistically significant correlation at 99% confidence level between a casualty's gender and age (see Table 3). Table 4 shows the correlation coefficients between daylight, weather and road surface condition, which also were not found to be statistically significantly correlated at 99% confidence level. These results suggest that speed limit, geometric design, sociodemographic characteristics and meteorological variables can be considered as independent values in the three BLRMs. However, the BLRM outcomes for number of lanes on approach and half width on approach should be interpreted with caution because of the high statistically significant correlation between these variables.

6.2. Dimension reduction

PCA was conducted in order to group the geometric design variables by reducing the dimensions. The number of factors was determined from the graph of eigenvalues and factor numbers by identifying those located with an eigenvalue of greater or equal to 1.00. In this analysis, two factors were determined from seven variables (Fig. 3).

When embarking on dimension reduction, the factors were assumed to be correlated. In this research, the non-parametric correlation matrix proved that certain variables, namely number of lanes on approach and half width on approach, were statistically significantly correlated at the 99% confidence level. Therefore, Promax with Kaiser Normalization in oblique rotation was applied. This assumption needed to be checked and corrected based on the result of the component correlation matrix as follows: the correlation between factor one and two was found to be 0.34, which lies just outside the recommended range (Tabachnick et al., 2014). This suggests that for this dataset Promax with Kaiser Normalization oblique rotation was the correct approach for the PCA.

For each factor, the loadings of the variables were determined by using the pattern matrix (see Table 5). Factor 1 “*Approach Capacity*” was characterized by association with the loadings of number of lanes on approach, half width on approach, entry path radius and number of flare lanes on approach. Factor 2 “*Size of Roundabout*” was associated with the statistically significant variables number of arms, type of roundabout and number of circulating lanes. There was no overlap found in the pattern matrix as all variables were statistically significantly located in their separate factors.

For further understanding, the reliability test was carried out in order to determine the internal consistency between the variables included in the same factor. Cronbach's Alpha values for *Approach Capacity* (0.07) and *Size of Roundabout* (0.63) were both below Tavakol and Dennick's (2011) recommend minimum value of 0.7. The lower alpha value means that there is a low internal consistency between the variables generated in the same factors. This result also proved the independence between the geometric design variables.

6.3. Binary logistic regression models

The dependent variable of the BLRM is the severity of cyclist casualty, which was coded as a binary variable where slight = 0 and serious = 1. The slight cyclist casualty category was chosen as the base level of the model to investigate in detail the influencing variables on serious casualties. The level of statistical significance was set at 95%, which means that variables in the model have a p-value equal to or less than 0.05 (see Tables 6, 7, 8).

Peduzzi et al. (1996) stated that the recommended minimum number of EPV should be 10 in BLRM. The number of events (number of serious casualties) was 69 in this study (see Section 5), suggesting that a maximum of seven variables could be included in the BLRM. On the other hand, the literature accepts that the minimum of 10 EPV is only a rule-of-thumb; therefore, this study aimed to generate
a BLRM with a number of statistically significant variables in the range of 7 up to a maximum of 10.

Table 2
Spearman's rho correlation results of speed limit and geometric design parameters.

Variable	1	2	3	4	5	6	7	8
1. Speed limit	1.00							
2. Number of lanes on approach	0.33**	1.00						
3. Half width on approach	0.23**	0.76**	1.00					
4. Entry path radius	−0.09	0.19**	0.23**	1.00				
5. Number of arms	0.17**	0.17**	0.18**	−0.03	1.00			
6. Number of flare lanes on approach	0.30**	0.61*	0.58**	0.21**	0.08	1.00		
7. Type of roundabout	0.20**	0.26**	0.34**	0.00	0.41**	0.26**	1.00	
8. Number of circulating lanes	0.36**	0.42**	0.37**	0.07	0.35**	0.46**	0.41**	1.00

* Statistically significant at 95% confidence level.
**Statistically significant at 99% confidence level.

In order to achieve this, the BLRM analysis was carried out in three steps in order to reduce the number of variables appropriately. Speed limit, sociodemographic characteristics and meteorological conditions were located in BLRM1. Geometric design variables were considered in BLRM2. In BLRM3, the factors generated from the dimension reduction were included as well as speed limit, sociodemographic characteristics and meteorological conditions. In BLRM1, only speed limit emerged as being statistically significant at the 95% confidence level (see Table 6). The signs of the coefficients were considered important. An odds ratio of 1.02 for speed limit suggests that a unit increase in speed limit increases the probability of a serious casualty for cyclists at roundabouts.

Table 3
Point biserial correlation results of sociodemographic characteristics

Variable	1	2
1. Gender of casualty	1.00	
2. Age of casualty	0.11**	1.00

**Statistically significant at 99% confidence level

Table 4
Cramer's V correlation results of meteorological variables

Variable	1	2	3
1. Daylight	1.00		
2. Weather	0.24**	1.00	
3. Road surface condition	0.23**	0.46**	1.00

**Statistically significant at 99% confidence level

The BLRM2 analysis was carried out to investigate the impact of geometric design variables on cyclist casualty severity (see Table 7). The results suggest that number of lanes on approach and entry path radius were statistically significant at the 95% confidence level with odds ratios of 4.97 and 1.04, respectively. This means that a higher number of lanes and a higher entry path radius increased the probability of serious casualty severity for cyclists at roundabouts.

Regarding BLRM1 and BLRM2, speed limit and entry path radius with the odds ratios of 1.02 and 1.04, respectively, were statistically significant at 95% confidence level, however their impact on casualty severity of cyclists at roundabouts is relatively small. This needs further investigation in order to gain a deeper understanding of the impacts of the speed and entry path radius.

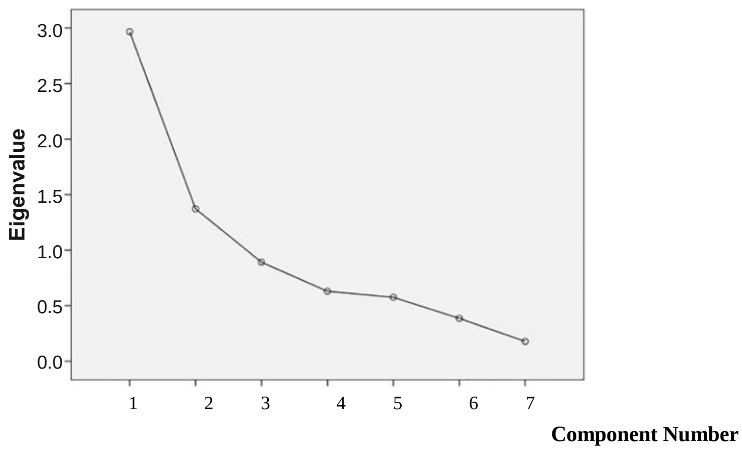

Fig. 3. Eigenvalues of each factor numbers.

Table 5
Pattern Matrix[a]

Variables	Factor 1 Cronbach's Alpha (0.07) Approach Capacity	Factor 2 Cronbach's Alpha (0.63) Size of Roundabout
Number of lanes on approach	**0.87**	0.05
Half width on approach	**0.85**	0.05
Entry path radius	**0.51**	-0.36
Number of arms	-0.21	**0.85**
Approach number of flare lanes	**0.82**	0.02
Type of roundabout	0.04	**0.77**
Number of circulating lanes	0.33	**0.58**

a. Rotation converged in 3 iterations.

Table 6
The results of binary logistic regression model for speed limit, sociodemographic characteristics and meteorological variables

Casualty	Coefficient	P ≥|z|	Odds Ratio	95% Confidence Interval for Odds Ratio	
				Lower	Upper
Speed limit	**0.02**	**0.02****	**1.02****	**1.00**	**1.05**
Gender of casualty	-0.27	0.48	0.76	0.36	1.62

Age of casualty	0.01	0.24	1.01	0.99	1.03
Daylight	-0.22	0.52	0.81	0.42	1.56
Weather	-0.22	0.56	0.80	0.39	1.68
Road surface condition	-0.22	0.49	0.81	0.44	1.49
Constants	-2.49	0.00	0.08		

***Statistically significant at 95% confidence level*

Table 7
The results of binary logistic regression model for geometric design variables

Casualty	Coefficient	P ≥|z|	Odds Ratio	95% Confidence Interval for Odds Ratio	
				Lower	Upper
Number of lanes on approach	**1.60**	**0.01****	**4.97****	**1.55**	**15.91**
Half width on approach	-0.22	0.18	0.80	0.58	1.11
Entry path radius	**0.04**	**0.00****	**1.04****	**1.03**	**1.06**
Number of arms	0.11	0.64	1.11	0.71	1.73
Number of flare lanes on approach	-0.32	0.32	0.72	0.38	1.36
Type of roundabout	-0.65	0.07	0.52	0.26	1.06
Number of circulating lanes	0.53	0.12	1.69	0.88	3.26
Constants	-5.72	0.00	0.00		

***Statistically significant at 95% confidence level*

Table 8
The results of binary logistic regression model for factors

Casualty	Coefficient	P ≥|z|	Odds Ratio	95% Confidence Interval for Odds Ratio	
				Lower	Upper
Speed limit	0.02	0.22	1.02	0.99	1.04
Gender of casualty	-0.34	0.38	0.71	0.33	1.53
Age of casualty	0.01	0.38	1.01	0.99	1.03
Daylight	-0.15	0.67	0.86	0.43	1.71
Weather	-0.12	0.76	0.89	0.41	1.91
Road surface condition	-0.43	0.21	0.65	0.33	1.28
Approach capacity	**0.62**	**0.00****	**1.86****	**1.40**	**2.47**
Size of roundabout	-0.29	0.06	0.75	0.55	1.01
Constants	-2.14	0.00	0.12		

***Statistically significant at 95% confidence level*

Finally, speed limit, cyclist age and gender, daylight, weather and road surface condition were considered with the factors generated from dimension reduction, which were *Approach Capacity* and *Size of Roundabout*, in BLRM3 to investigate the impact of *Approach Capacity* and *Size of Roundabout* on cyclist casualty severity. The results presented in Table 8 demonstrated that *Approach Capacity* was statistically significant at the 95% confidence level with a p-value of 0.00 and an odds ratio of 1.86. This suggests that a unit increase in the *Approach Capacity* increases the cyclist casualty severity at roundabouts.

7. Discussion

Thirteen variables, including geometric design, sociodemographic characteristics, speed limit and meteorological conditions were investigated to understand whether they played a statistically significant role in the severity of cyclist casualty at roundabouts.

According to BLRM1, speed limit had a statistically significant influence on serious casualty severity for cyclists. The only study included speed limit as a variable in casualty severity analysis was carried by Jensen (2017), however this study carried a before after analysis of converting signalised junctions to roundabouts regarding to speed limit. The study (Jensen, 2017) stated that converting an intersection to a roundabout with a 70 km/h (or higher) speed limit increased safety for cyclists. Our research suggests that increasing the speed limit makes roundabouts less safe for cyclists.

Daniels et al. (2010) found that the number of severe casualties increases for the higher age groups for all road user types at roundabouts. In terms of all road types, Evans (2004) found that there was a statistically significant equal probability of fatal casualty of female and male cyclists and the severity increases for older age groups (Bedard et al., 2002; Evans, 2004). Our research showed no statistical significance for either age or gender in the cyclist casualty severity analysis. One reason for this apparent inconsistency with the literature may be due to our study only considering cyclist casualty severity at roundabouts rather than at all junction types; another reason might be due to the different cycling behaviours of age and gender groups in different study regions creating more variance. Weather and road surface conditions were expected to have an impact on cyclist casualty severity as rain, ice, and snow reduce traction on the road surface for both cyclists and drivers, and may increase the serious or slight casualties due to the potential loss of control. In terms of daylight, previous research by Daniels et al. (2010) indicated that the probability of serious casualty severity for all types of road user was higher at night at roundabouts. The results of our research illustrated that daylight conditions did not have any statistical significance in the results. The reason for the difference in the results here with Daniels et al. (2010) may be due to there being different cyclist flows in the respective regions. The cyclist flow at the time of the accident was not known in the study reported here and therefore could not be considered. In addition, weather and road surface condition did not show a statistically significant impact on cyclist casualty severity at roundabouts. This particular result requires further study because there might be fewer cyclists on the road during poor weather and night conditions, a variable that affects the statistical sampling.

BLRM2 included geometric design parameters and the results suggested that number of lanes on approach and entry path radius were statistically significant in the regression analysis. However, other geometric design variables (i.e. half width on approach, number of arms, number of flare lanes on approach, type of roundabout and number of circulating lanes) were not statistically significant.

The results of this study suggest that a higher number of lanes on the approach arm is consistent with a higher number of conflict points, which increases the probability of severe cyclist casualties at roundabouts. The reason for this may be due to the relative positioning of cyclists and drivers on more than one lane, which increases the probability of masking of the cyclist especially when traffic has a high proportion of busses and heavy goods vehicles. Furthermore, the Spearman's rho correlation matrix (see Table 2) suggested that there was a statistically significant positive and high correlation between number of lanes on approach and half width on approach; however, half width on approach did not show any statistical significance in the BLRM2. In addition, there was only a moderate positive correlation between number of lanes on approach and number of flare lanes on approach. Likewise, the BLRM2 outcome of number of flare lanes on approach was not statistically significant. In essence, the correlation analysis provided an indication of groups of variables that were weakly associated with each other despite not emerging as statistically significant in the BLRM2. The possible reason for this result was that number of lanes on approach might be emerging as a dominant representative of correlated variables considered in the same BLRM2.

The drive through curve, which is related to entry path radius, is known to be significant in cyclist collision occurrence at roundabouts (Hels & Orozova-Bekkevold, 2007). The results of the current study show, with statistically significance at 95% confidence level, that higher entry path radius also increases the probability of serious casualties for cyclists. Entry path radius influences the speed of a vehicle on approach and at entry locations (DfT, 2007). This research result is consistent with higher speed along with higher entry path radius being contributors to increasing cyclist casualty severity at roundabouts. This outcome is consistent with the result of BLRM1, because the entry path radius can be considered as a proxy for speed limit.

Finally, the impact of the generated factors (*Approach Capacity* and *Size of Roundabout*) were investigated in BLRM3, which included speed limit, sociodemographic characteristics and meteorological-related variables. The results showed that only *Approach Capacity* has a statistically significant impact on casualty severity for cyclists. A unit increase in *Approach Capacity* increased the probability of a serious casualty, enabling vehicles to travel faster. This, as previously suggested (Lawton et al., 2003), confirms the need for tighter approach and entry geometry to increase cyclist safety at roundabouts. Compared to BLRM1, the statistical significance of speed limit disappeared in BLRM3. The reason for this result might be that *Approach Capacity* is a proxy for vehicle speed and is more dominant in this form of the model. It is suggested that *Approach Capacity*, as a numerical traffic related variable, should be collected and applied in regression models in future studies to ensure an improvement in the robustness of the results.

Jensen (2017) reported that single lane roundabouts with a central island radius of 20–40m are safer than smaller or larger single lane roundabouts, in terms of cyclist casualty occurrence. In the current study, the impact of the variable '*Size of*

Roundabout' generated in the PCA did not have a statistically significant influence in BLRM3. This result was expected since the variables, which created the factor named '*Size of Roundabout*', were not statistically significant when considered as individual variables (see Table 8). This concurs with the level of cyclist casualty severity being related to variables other than the size of roundabouts.

8. Limitations

A standard way to measure the entry path radius is not described in specific terms in the DMRB (DfT, 2007); however, all measurements were carried out by Akgun to maintain consistency. For further studies, it is recommended that entry path radius should be revisited and the number of cyclist casualty records increased.

9. Conclusions

The conclusions of this paper can be summarized as eight key messages:

1. A higher speed limit makes roundabouts less safe for cyclists (odds ratio 1.02).
2. Sociodemographic characteristics and meteorological variables were not found to influence cyclist casualty severity at the roundabouts considered in this study.
3. The severity of cyclist casualty at roundabouts was predominantly influenced by the number of lanes on approach and entry path radius.
4. The probability of a serious casualty increases by approximately five times (odds ratio 4.97) for each additional lane on approach.
5. While number of lanes on approach and half width on approach were statistically significantly correlated, half width on approach was found not to be statistically significant in the BLRM2.
6. Higher entry path radius (propensity to increase speed into the roundabout) increases the probability of a serious casualty by 4% (odds ratio 1.04).
7. The factor '*Approach Capacity*' (also a proxy for the propensity to increase speed into the roundabout), generated from the dimension reduction process, increases the probability of casualty severity of a cyclist by 86% (odds ratio 1.86); and finally,
8. Both the number of lanes on approach and entry path radius emerged as statistically significant variables in the same factor generated from PCA.

10. Impact on industry

Designers of roundabouts and local authorities should give more consideration to Approach Capacity related variables, such as the number of lanes on approach and entry path radius, with regard to the future design of roundabouts especially if levels of cyclist flows increase. However, it is acknowledged that changing the geometric design of existing roundabouts might not be an economical solution (Montella, 2011). This raises the important issue of modifying the layout of the highway on entry to the roundabouts. These improvements are particularly important at multilane roads and should include channelization, islands and speed limits. In addition, further research should focus on the interaction between drivers and cyclists at approach and entry locations using video techniques.

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