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Analysing truck harsh braking incidents to study roundabout accident risk

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ABSTRACT

In order to reduce accident risk, highway authorities prioritise maintenance budgets partly based upon previous accident history. However, as accident rates have continued to fall, this approach has become problematic as accident 'black spots' have been treated and the number of accidents at any individual site has fallen, making previous accident history a less reliable indicator of future accident risk. Another way of identifying sites of higher accident risk might be to identify near-miss accidents (where an accident nearly happened but was avoided). The principal aim of this paper is to analyze potentially unsafe truck driving conditions from counts of Harsh Braking Incidents (HBIs) at roundabouts and compare the results to similar, previous studies of accident numbers at the same sites, to explore if HBIs can be studied as a surrogate for accidents. This is achieved by processing truck telematics data with geo-referenced incidents of harsh braking. Models are then developed to characterise the relationships between truck HBIs and geometric and traffic variables. These HBIs are likely to occur more often than accidents and may, therefore, be useful in identifying sites with high accident risk. Based on the results of this study, it can be concluded that HBIs are influenced by traffic and geometric variables in a similar way to accidents; therefore they may be useful in considering accident risk at roundabouts. They are a source of higher volumes of data than accidents, which is important in considering changes or trends in accident risk over time. The results showed that random-parameters count data models provide better goodness of fit compared to fixed-parameters models and more variables were found to be significant, giving a better prediction of events.

1. Introduction

In the UK, overall road accident rates have been falling for many years (Department for Transport, 2014). In efforts to continue this reduction, highway authorities maintain budgets for road safety improvements and these must be prioritised to those locations where safety measures, such as junction improvements and resurfacing, will be most effective. In the past, priority could be given to sites with poor accident records, or 'black spots'. As accident rates have fallen, these locations have become less apparent and additional methods are required to prioritise expenditure on road safety.

Nowadays the vehicles using the road networks have become more sophisticated, including in the number of sensors recording data for logistics, engine management, and maintenance purposes. It may be feasible that, in some cases, these data could also be used by highway authorities to provide information about the road networks. Amongst these data, truck fleet management companies often collect records of the position of vehicles within their fleet; this is used, primarily, for logistical reasons but can also be processed and combined with other data (e.g. engine speed or gear selection) to provide information about driver behaviour, for instance for use in driver training to improve fuel economy (see for instance Microlise, 2016). During the years 2011 and 2012, a fleet of approximately 8000 trucks in the UK had the Global Positioning System (GPS) and Control Area Network (CAN) installed and supervised by Microlise Ltd. Position data can be processed to record acceleration and identify harsh braking incidents (HBIs). A large number of HBIs (195,297) were recorded over the UK roads and intersections during the 2-years. These HBIs can be seen to cluster at some roundabouts. Fig. 1 shows a grade-separated roundabout, the red buttons indicate the 138 accidents recorded over an 11-year period (2002–2012), and the blue buttons indicate the 728 HBIs over a 2-year period (2011–2012). The number of HBIs is much higher than the number of accidents. Where the HBIs are due to unsafe driving, they may represent accident near-misses. The principal aim of this paper is to analyze potentially unsafe truck driving conditions from counts of Harsh Braking Incidents (HBIs) at roundabouts and compare the results to similar, previous studies of accident numbers at the same sites, to explore if HBIs can be studied as a surrogate for accidents.

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Fig. 1. Grade-separated roundabout (J28 on M1 motorway, UK) with accident (left) and truck HBI (right) positions.

2. Literature review

Based on previous studies different definitions are available for harsh braking events, for instance GEOTAB INC. (2015) defines harsh deceleration "as acceleration greater than 4.76 m/s^2 (0.49 g) in the backward direction", and Teletrac (2016) states that it is "The number of heavy braking incidents based on G-force and type of vehicle (light, medium, or heavy)". In the euroFOT project the "incident is defined as harsh braking at decelerations of more than 4 m/s^2" (Kessler et al., 2012). A list of different deceleration levels defined as harsh braking events is shown in Table 1. The level of deceleration that constitutes harsh braking or an accident risk may be different for trucks compared to other vehicles and may also depend on load. Based on the studies in Table 1, the definition of harsh longitudinal deceleration varies from 0.2 g (1.96 m/s^2) to 0.86 g (8.44 m/s^2) with a majority indicating a deceleration of > 0.5 g (4.9 m/s^2). In addition, rate of change of acceleration, or 'jerk', has been identified as a risk factor (Bagdadi and Várhelyi, 2011) but this is not recorded in the data analysed in this paper.

One aim of a transportation department is safety: "To contribute to better safety, security and health and longer life-expectancy through reducing the risk of death, injury or illness arising from transport, and promoting travel modes that are beneficial to health" (Lee and Humphrey, 2011). The use of roundabouts improves intersection safety by reducing or changing conflict types, reducing accident severity, and leading drivers to reduce speeds (Highways Agency (2007a,b; Rodegerdts et al. (2010); SETRA, 1998). For this reason, in the UK roundabouts are widely used instead of other junction types. However, these characteristics cannot prevent accidents from occurring, and a significant number of all vehicle and truck accidents are recorded at roundabouts.

Size, weight, and manoeuvring of a truck is different from passenger cars, and it is essential to consider their safety at roundabouts. The geometric design of roundabouts is a sensitive issue, as any sudden change in geometric design leads the roundabouts to be less safe (Kennedy, 2007). Truck rollover accidents are common at roundabouts (Kemp et al., 1978). Trucks overturn at roundabouts because of extreme speed or hard braking, while they are on adverse super elevation

Table 1
Summary of the deceleration level by previous studies for triggering a harsh braking record.

Study	Longitudinal Deceleration*	Notes
Dingus et al. (2006)	> 0.5 g	In addition to this deceleration they used longitudinal deceleration as a dependent variable to define near-miss accidents at > 0.6 g
Klauer et al. (2006)	0.44 g	Inattentive driving is the cause for these decelerations
Fitch et al. (2009)	0.53 g and 0.68 g	During lane changes, four drivers braked at 0.68 g, and 12 drivers braked at 0.53 g
GEOTAB INC (2015)	> 0.49 g	Straight and turn harsh deceleration
Kessler et al. (2012)	> 0.4 g	euroFOT project
Olson et al. (2009)	> 0.35 g and > 0.2 g	For Drowsy Driver Warning System Field Operational Test (DDWS FOT) and NTD (Naturalistic Truck Driving Study), respectively.
Blanco et al. (2011)	> 0.2 g	For 97 trucks, safety critical events increase with increasing driving and working hours
Fazeen et al. (2012)	> 0.3 g	This study used phone accelerometers within cars
Grygier et al. (2007)	0.75 g	For the stopping vehicle (truck) manoeuvre with speed 55 mph
Haque et al. (2016)	0.45 g, 0.5 g, and 0.52 g	For no phone, hand-held, phone and hands-free conversation at single lane roundabouts
Simons-Morton et al. (2009)	≤0.45 g	The majority of this braking occurred because of driver misjudgement
Harbluk et al. (2007)	> 0.25 g	85% of the braking recorded at an intersection
Bayan et al. (2009)	0.75 g, 0.72 g, and 0.52 g	These decelerations are recorded in dry surface condition speed 60 mph, in dry surface condition speed 30 mph, and on wet surface condition speed 30 mph, respectively
Greibe (2007)	0.86 g and 0.81 g	This deceleration recorded in dry and wet surface conditions, resepectively.
	0.75 g and 0.71 g	This deceleration recorded for experienced driver on dry and wet surface respectively, and inexperienced driver recorded harsh braking incident at adeceleration rate by less than 10% when it is compared to the experienced driver
Lee et al. (2007)	0.51 g and 0.66 g	At intersections the deceleration rate was for incident and near-miss accidents, respectively.
Inman et al. (2008)	0.78 g and 0.67 g	At an intersection for simulation and test track study, respectively
Klauer et al. (2009)	> 0.3 g	Different braking decelerations were recorded in this study and catagorised as safe, moderately safe and unsafe driving in different ranges of deceleration. Most near-miss accidents occurred because of inappropiate braking and speed
Benmimoun et al. (2011)	0.61 g	For cars and trucks, with regard to vehicle dynamics and at a low threshold speed < 50 km/h
	0.41 g	For cars and trucks, with regard to vehicle dynamics and at a low threshold at speed 50–150 km/h
	0.82 g and 0.71 g	For cars and trucks, respectively, with respect to vehicle dynamics at high threshold
	0.70 g	For cars and trucks with respect to the distance behaviour at high threshold

* multiply by 9.81 to convert to m/s^2.

(Kennedy, 2007). In addition, Arndt (1991) states that roundabouts with high inscribed circle diameter (ICD) allow high speed, and, when there is a high cross-fall in the circulatory lanes, this can lead to trucks becoming unbalanced. Weber and Button, 2009, in a study for accommodating small and large trucks at roundabouts, stated that issues with trucks at roundabouts centre on accommodating them within the available geometry. Thus the geometrical design of the roundabout can highly influence truck drivers and may lead them to record HBIs. In such cases roundabouts become less safe for trucks.

Previous studies (Maycock and Hall, 1984; Guichet, 1997; Montella, 2007; Kim and Choi, 2013; Harper and Dunn, 2005; Turner et al., 2006; Brüde and Larsson, 2000; Šenk and Ambros, 2011; Daniels et al., 2010; Rodegerdts et al., 2010) identified the influence of traffic and geometric variables on total accidents at roundabouts using fixed-parameters negative binomial models, and they found significant results regarding the influence of these variables. Therefore, in this study, geometric and traffic variables (AADT, and percentage of truck traffic) were selected to identify their influence on truck HBIs, but random parameter negative binomial models were used instead of fixed parameter models because, if parameters are estimated as fixed, the result may be biased, and possibly, incorrect conclusions will be drawn with respect to the independent variables (Lord and Mannering, 2010). For the same reason, random-parameters count data models were introduced by researchers to study accidents at road segments (Milton et al., 2008; Anastasopoulos and Mannering, 2009; El-Basyouny and Sayed, 2009; Garnowski and Manner, 2011; Ukkusuri et al., 2011; Venkataraman, 2014) and at roundabouts (Kamla et al., 2016). The random-parameters models used by the above authors are an addition to random-effects models. However, in the random effects model only the constant of the model will be random across the observations, while random-parameters models permit some or all of the independent variables to be random across the observations (Lord and Mannering, 2010). One objective of the analysis presented in this paper is to relate the number of truck HBIs to a range of possible explanatory (geometric and traffic) variables, and hence to determine any relationships which could be used to explore site-specific safety risks, using the random-parameters negative binomial approach.

3. Methodology

3.1. Procedure

A sample of truck HBI data was supplied by Microlise Ltd. It includes speed, date, time, longitude, latitude, and date for 195,297 HBIs over UK roads and intersections during the 2-years, 2011 and 2012. Using an earth point program, which displays excel files on Google Earth, the position data (latitude and longitude coordinates) are imported to Google Earth. Microlise Ltd. defines harsh braking as a sudden reduction in the speed of a truck which is deemed to be excessive and likely caused by bad forward planning for the situation ahead (roundabout, traffic lights changing, junctions, etc.). Any point which records a deceleration above a specified magnitude over a specified duration is flagged and its location is recorded. The default value varies based on customer requirements (i.e. type of operation, type/size of truck etc.), and are a deceleration of 2.22 (heavy truck) and 4.44 m/s^2 (van or light truck). Therefore, if the speed of a heavy truck is reduced by 8 km/h over one second, the unit records a harsh braking event. On a test track, using a Microlise Ltd. truck (3.5 t) equipped with smartphone accelerometers, HBIs were recorded at maximum decelerations of 8.51–8.60 m/s^2 at different speeds. This indicates that the threshold set by Microlise Ltd. is valid, as it is less than the maximum deceleration measured from the trials identified by smartphone accelerations. According to the result of previous studies shown in Table 1 the harsh braking longitudinal deceleration varies from 0.2 g (1.96 m/s^2) to 0.86 g (8.44 m/s^2). The thresholds set by Microlise Ltd. are within the range for previous studies. Thus the HBI data from Microlise Ltd. is suitable for the purpose of achieving the aims and objectives of the study.

For each location the number of HBIs was counted manually for each arm of the selected roundabout and for the circulatory lanes, from Google Earth. The distances between any two points recorded at roundabouts were calculated using the following formula (Lentz, 2008)[1]:

$$D = R_E \times \cos^{-1}((\cos(R(90 - Lat_1)) \times (\cos R(90 - Lat_2)) + (\sin(R(90 - Lat_1)) \times (\sin(R(90 - Lat_2)) \times (\cos R(Long_1 - Long_2)))) \quad (1)$$

3.2. Model estimation

The random parameters model allows for unobserved heterogeneity from one road section to another and the methodological approach to achieve this is discussed in detail by Washington et al. (2003) and Anastasopoulos and Mannering (2009).

For a road segment (road segment or intersection including roundabouts) having (i) observations and having a number of accidents (n_i) (both non-negative, discrete, count data) the Poisson model can be written as:

$$P(n_i) = \frac{EXP(-\lambda_i)\lambda_i^{ni}}{n_i!} \quad (2)$$

where λ_i is the factor used in the Poisson model for observation i, and $P(n_i)$ is observation i's predicted number of accidents.

The predicted number of accidents, specified by Poisson regression λ_i is related to the dependant variables using a log-linear function:

$$\lambda_i = EXP(\beta X_i) \quad (3)$$

where X_i is the independent variable i, and β is the coefficient of the independent variable.

The Poisson regression assumes that variance and mean are equal and this cannot always be applied to the data. If the two are not equal, either the data is under dispersed in which case the mean is greater than variance, or over-dispersed, and the mean will be less than variance. Either results in an incorrect standard error of the independent variables, and hence, a wrong conclusion could be drawn. In these cases, it is essential to re-write the model using a negative binomial distribution, which does not have this restriction. Instead the variance varies from the mean by adding the term $EXP(\varepsilon i)$ (a gamma-distributed error term with mean 1 and variance α^2) to Eq. (3). The resulting equation will be:

$$\lambda_i = EXP(\beta X_i + \varepsilon_i) \quad (4)$$

The form of the negative binomial distribution function is (Washington et al., 2003):

$$P(n_i) = \left[\frac{\frac{1}{\alpha}}{\left(\frac{1}{\alpha}\right) + \lambda_i}\right]^{\frac{1}{\alpha}} \frac{\Gamma\left[\left(\frac{1}{\alpha}\right) + n_i\right]}{\Gamma\left(\frac{1}{\alpha}\right) n_i!} \left[\frac{\lambda_i}{\left(\frac{1}{\alpha}\right) + \lambda_i}\right]^{n_i} \quad (5)$$

where $\Gamma(.)$ is a gamma function

Greene (2007) produced "simulated maximum likelihood estimation" which accounts for heterogeneity (i.e. independent variables that may change across the road segments or intersections), which enhances Poisson and negative binomial count-data models with random parameters and allows λ to change as a function of the mean in the negative binomial distribution. This maximum likelihood estimation for the random parameter count data is independent, so draws are used to

[1] Where: D = Distance is in km, R_E = Earth Radius which is 6378.135 km, R = Radians, Lat_1 and Lat_2 are the latitude of the first point and second point in decimal degrees, respectively. $Long_1$ and $Long_2$ are the longitude of the first point and second point in decimal degrees, respectively.

Table 2a
Whole roundabout characteristics.

Number of arms				Signalisation			Number of lanes		Type of grade	
3-arm	4-arm	5-arm	6-arm	Traffic signals	No traffic signals	Partially signalised	2-lane	3-lane	At-grade	Grade-separated
12	39	12	7	20	28	22	39	31	19	51

overcome this problem. "Halton draws"[2] are commonly used for numerical simulation; 200 Halton draws were used in this study. Bhat (2001), Bhat (2003), and Train (1999) compared Halton sequences[3] to pseudo-random sequences, and stated that the performance of Halton sequences is better compared to random sequences, because the unit interval is filled by these draws equally and more intensely and in a good sequence. They state that fewer draws of Halton sequences provide better coverage and better accuracy compared to pseudo-random sequences.

In order to let variables change across the observations in the negative binomial and Poisson count data models, the independent variables are drawn as:

$$\beta_i = \beta + \varphi_i \tag{6}$$

where φ_i is "a randomly distributed term (for example a normally distributed term with mean 0 and variance α^2)" (Anastasopoulos and Mannering, 2009). The Poisson model will be written as $\lambda_i/\varphi_i = EXP(\beta X_i)$, and the negative binomial model will be written as $\lambda_i/\varphi_i = EXP(\beta X_i + \varepsilon i)$. The log-likelihood will be:

$$LL = \sum_{\forall i} ln \int_{\varphi_i} g(\varphi_i) P\left(\frac{n_i}{\varphi_i}\right) d\varphi_i \tag{7}$$

where $g(\cdot)$ is the probability density function of φ_i (Anastasopoulos and Mannering, 2009).

In Poisson and negative binomial model estimation, one can derive the marginal effect, which illustrates the relative magnitude between the dependent and independent variables based on parameter estimates (Anastasopoulos and Mannering, 2009). The marginal effect is the variation in the number of dependant variables due to one unit change in the independent variables X_i. It is computed as partial derivative, $\partial\lambda_i/\partial x$ where λ_i is defined in Eqs. (3) and (4),(for Poisson, and negative binomial with fixed parameters expression, respectively) or as $\lambda_i/\varphi_i = EXP(\beta X_i)$, and $\lambda_i/\varphi_i = EXP(\beta X_i + \varepsilon i)$ (for Poisson, negative binomial with random-parameters models, respectively) (Anastasopoulos and Mannering, 2009).

3.3. Model evaluation

Assessments were made to select the most appropriate and best fitting models. Firstly, the model is evaluated according to the significance of the variables included in the model. The estimated regression coefficient for each independent variable should be statistically significant. Usually, the *t*-test is used to test the significance of the coefficients, three t-statistics are available for testing the significance of the variables, they are 1.65, 1.96, and 2.58 (for 90%, 95%, and 99% significance levels, respectively).

The likelihood ratio test was used to compare fixed- and random-parameter models using the likelihoods at convergence. The test statistic is chi-square , χ^2:

$$\chi^2 = -2[LL(\beta_F) - LL(\beta_{RP})] \tag{8}$$

Where $LL(\beta_F)$ is the log likelihood at convergence of the fixed-parameters negative binomial model, and $LL(\beta_{RP})$ is the log likelihood of the random-parameter negative binomial model (Washington et al., 2003). The statistic is χ^2 distributed with the degrees of freedom equal to the number of parameters that are found to be random.

The two models were also compared using the relationship between actual mean values and predicted values of the response variables for both random- and fixed-parameters models.

4. Data

This research used position data collected by Microlise Ltd for 8000 trucks in the United Kingdom (UK), over a two year period 2011 and 2012. To test the hypothesis that these incidents could represent accident near misses and therefore, increased accident risk, 70 roundabouts (with 284 approaches) with low and high occurrence of HBIs were selected. Tables 2a–c illustrate the whole roundabout, within circulatory lanes, and roundabout approach characteristics, of the roundabouts, respectively.

Average annual daily traffic (AADT) and the percentage of truck traffic (percentage AADTT) were acquired from the Department for Transport, Traffic Counts (DFT, 2016) for the years 2011 and 2012. Accident data were collected from the STATS19 database of accidents on public roads in United Kingdom, including human injury and fatality, as recorded by police officers, for the eleven years 2002–2012. This includes all injury accidents reported by police for all vehicles. Location is recorded on the STATS19 form using Ordnance Survey grid reference (OSGR), usually to the nearest 10 m. There is also the opportunity to record if the accident is at or near a roundabout or on the 'slip road' approach or exit from a roundabout and if a vehicle is leaving or entering a roundabout. However, for these records, the accident position was recorded according to the OSGR position.

Roundabout entry width, circulatory roadway width, and inscribed circle diameter (ICD) were calculated for the selected roundabouts from aerial photographs on an on-line mapping site. Fig. 2 shows the roundabout geometric information. Summary statistics of all variables are presented in Table 3. These variables have been chosen because researchers have demonstrated that they can have a significant effect on the safety of roundabouts (Rodegerdts et al., 2010; Rodegerdts et al., 2007; Maycock and Hall, 1984; Retting, 2006; Harper and Dunn, 2005; Brüde and Larsson, 2000; Kim and Choi, 2013).

Washington et al. (2003) stated that in regression analysis having categorical variables, n-1 indicator values must be generated to represent n levels; if not it will cause collinearity with the constant of the model. For instance, in this study traffic signalisation in the whole roundabout and within the circulatory lanes can be signalised, un-signalised, or partially signalised, and a categorical variable was used only for signalised and un-signalised, because if we have a three-category variable we cannot estimate three indicators, since they will sum to one and be collinear with the constant. Therefore, for a signalisation indicator (1 if signalised; 0 otherwise) and (1 if un-signalised; 0 otherwise), the beta (regression coefficient) will tell us the effect relative to partially signalised intersections. The same approach is taken for the number of arms, as there are three, four, five and six-arm roundabouts, and for number of lanes, and other categorical variables. Note that in this study a roundabout is considered partially signalised when one or more of the approaches and circulatory lanes are signalised but not all.

[2] "Halton draws are sequences used to generate deterministically constructed, nearly uniformly distributed points in the interval [0, 1], that appear to be random" (Anastasopoulos and Mannering, 2009).

[3] "The standard Halton sequence is designed to span the domain of the S-dimensional unit cube uniformly and efficiently (the interval of each dimension of the unit cube is between 0 and 1)" (Bhat, 2003).

Table 2b
Characteristics of roundabouts within the circulatory lanes.

Signalisation			Number of lanes		Type of grade	
Traffic Signals	No Traffic Signals	Partially Signalised	2-lane	3-lane	At Grade	Grade Separated
21	30	19	40	30	19	51

4.1. Harsh braking incidents and position

Approach HBIs occurred at different distances from the entry line and at different speeds. In order to characterize the type of incidents by distance, the data were divided into three groups; within the roundabout circulatory lanes, on an approach within 100 m of the entry line, and > 100 m from the approach entry line.

This distance was chosen because most HBIs occurred within 100 m of the entry line; see Fig. 3 as an example. Some locations have a high number of incidents within the circulatory of the roundabouts; these locations are grade separated and they have high inscribed circle diameters, and most of them are signalized or partially signalized within the roundabout circulatory, which may be a contributory cause of harsh braking. More details about factors influencing HBIs will be addressed in model development. Some approaches have incidents beyond 100 m, usually when there is high percentage of truck traffic and high traffic volume. Table 4 illustrates the comparison between total and truck accidents and HBI positions. The highest number of HBIs and accidents occurred within 100 m of the entry line: 75% and 60% respectively. Only 12% of the HBIs occurred more than 100 m away from the entry line, while this is the case for only 7% of total and truck accidents. Some 32% and 36% of total and truck accidents, respectively, were recorded within the roundabout circulatory, which is significantly higher than the rate of HBIs within the circulatory lanes (13%). This means a greater percentage of accidents were recorded within the roundabout circulatory while a lower percentage was recorded on the approaches, compared to the HBI rates. Within 100 m distance of the entry line, the occurrence of HBI's was higher compared with accident rates (especially compared to truck accident rates).

5. Model development

In order to identify how traffic and geometric variables effect these HBIs, random- and fixed-parameters negative binomial (NB) count data models were investigated for the whole roundabout, within the circulatory lanes, and on the roundabout approaches. Table 5 presents the results of the estimated random- and fixed-parameters NB models. Table 6 shows the average marginal affects that result. It is clear that the results can be quite different for the two types of model.

The results show that for **whole roundabouts**, the log-likelihood at convergence for the random-parameters model is better compared to the fixed-parameters model; and according to its log-likelihood test ratio (the χ^2 statistic value Eq. (8) of 8.63 with three degrees of freedom) gives 97% confidence that the random-parameters model is statistically more significant than the fixed-parameters model. In addition, Fig. 4 identifies a better overall fit when actual values are related to predicted values for the random-parameters model relative to the fixed-parameters model.

Within the circulatory, the results show that the log-likelihood at convergence for the random-parameters model is better, as compared to the fixed-parameters model. Also, the log-likelihood test ratio (the χ^2 statistic value Eq. (8) = 22.8892 with two degrees of freedom) results in greater than 99.99% confidence that the random-parameters model is better. Furthermore, Fig. 5 illustrates a better overall fit with the random-parameters model when actual values are related to predicted values.

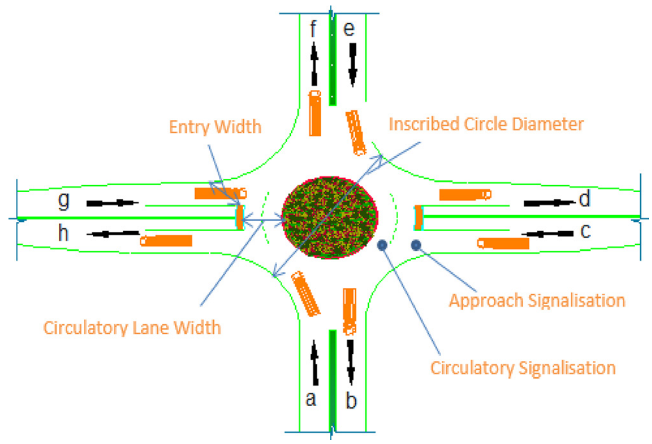

Fig. 2. Geometric elements of roundabouts.

At approaches, the log-likelihood at convergence for the random-parameters model is better, as compared to the fixed-parameters model. The χ^2 statistic value of Eq. (8) is 34.966 with three degrees of freedom. Thus there is greater than 99.99% confidence that the random-parameters model is better. Fig. 6 also illustrates a better overall fit with the random-parameters model when actual values are related to predicted values.

For each roundabout category all the variables presented in Table 3a–c were tested in order to find their significance.

For the whole roundabouts, the following variables were found to have a significant effect on increasing/decreasing HBIs, but their effect was fixed across the selected roundabouts in the random-parameters models:

- Circulatory lane width,
- Entry width,
- AADT, and
- Percentage of AADTT.

The following indicator variables were found to have significant random effects on increasing/decreasing HBIs at the selected whole roundabouts:

- Three-arm roundabouts,
- Signalised roundabouts, and
- Un-signalised roundabouts.

A parameter is considered random when the standard deviation of the parameter distribution is statistically different from zero (if the estimated standard deviation (SD) of the variable is not statistically different from zero then the variable is fixed across the observations).

Examining whole roundabouts, the effect of the three-arm indicator was varied across the observations having a normal distribution with a

Table 2c
Roundabout approach characteristics.

Signalisation		Number of lanes		Type of grade		Road class type		
Traffic signals	No traffic signals	2-lane	3- lane	At- grade	Grade-separated	A road	M road	B road
142	142	172	112	73	219	174	94	16

Table 3
Summary statistics of the HBIs, geometric and traffic variables.

Roundabout Category	Variable	Min	Max	Mean	Standard Deviation
a for whole roundabouts					
Whole Roundabouts	*HBI characteristics*				
	Dependent Variable: 2 -year number HBIs	0	764	152.6	180.2
	Geometric characteristics				
	Lane Number[a] (1 if lane number is 2; 0 if 3)	0.00	1.00	0.55	0.50
	Number of Arms(1 if arm number is 3; 0 otherwise)	0.00	1.00	0.17	0.38
	Number of Arms (1 if arm number is 4; 0 otherwise)	0.00	1.00	0.55	0.50
	Number of Arm (1 if arm number is 5; 0 otherwise)	0.00	1.00	0.13	0.34
	Inscribed Circle Diameter (m)	38.00	280.00	158.29	65.95
	Circulatory Lane Width (m)	6.00	15.00	10.65	1.83
	Entry Width[b] (m)	7.00	14.00	9.99	1.89
	Traffic Signal[c] (1 if signal; 0 otherwise)	0.00	1.00	0.29	0.46
	Traffic Signal[d] (1 if un-signal; 0 otherwise)	0.00	1.00	0.40	0.49
	Traffic characteristics				
	Average Annual Daily Traffic (AADT)[e]of All Vehicles	11170	137773	50840.86	27691.78
	Percentage Average Annual Daily Truck Traffic (AADTT)	2.18	22.53	6.97	3.26
b within circulatory lanes					
Within Circulatory	*HBI characteristics*				
	Dependent Variable: 2 -year number of HBIs	0	231	19.7	40.6
	Geometric Characteristics				
	Lane Number (1 if lane number is 2; 0 if 3)	0.00	1.00	0.57	0.50
	Inscribed Circle Diameter (m)	38	280	162.40	64.37
	Circulatory Lane Width (m)	6	15	10.67	1.86
	Traffic Signal (1 if is signal; 0 otherwise)	0.00	1.00	0.30	0.46
	Traffic Signal (1 if un-signal; 0 otherwise)	0.00	1.00	0.43	0.50
	Traffic Characteristics				
	Average Annual Daily Traffic (AADT) of All Vehicles	11170	137773	50840.86	27691.78
	Percentage Average Annual Daily Truck Traffic (AADTT)	2.18	22.53	6.97	3.26
c at approaches					
At Approaches	*HBI characteristics*				
	Dependent Variable: 2 -year number HBIs	0	325	31.1	54.5
	Geometric Characteristics				
	Lane Number (1 if lane number is 2; 0 if 3)	0.00	1.00	0.61	0.49
	Approach Entry Width (m)	5.26	20.00	9.99	2.40
	Traffic Signal (1 if is signal; 0 if un-signal),	0.00	1.00	0.50	0.50
	Type of Grade (1 if roundabout is grade-separated; 0 if at-grade)	0.00	1.00	0.74	0.44
	Traffic Characteristics				
	Average Annual Daily Traffic (AADT) of All Vehicles	1903	51201	12724.04	7382.41
	Percentage Average Annual Daily Truck Traffic (AADTT)	1.00	18.00	7.00	3.00

[a] Note that number of traffic moving lanes for the whole roundabout is the average number of lanes at approaches and within roundabout circulatory.
[b] Entry width for whole roundabout is the average approach entry width.
[c] A roundabout is considered signalised when it is signalised at approaches and within the circulatory.
[d] A roundabout is considered un-signalised when it is un-signalised at approaches and within the circulatory.
[e] Traffic volume for whole roundabout is the total approach traffic volume.

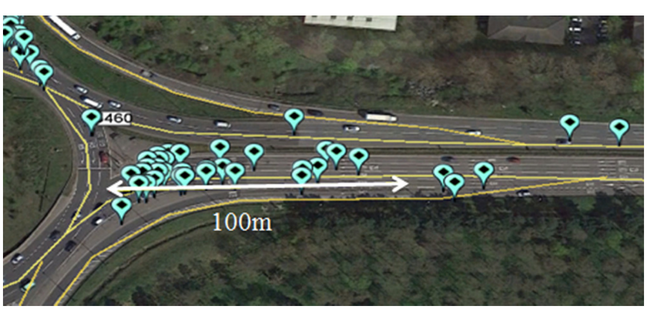

Fig. 3. HBI locations east of J21 on the motorway M1.

mean of 0.064 and a SD of 1.117. Based on this distribution, 52.3% of the three-arm roundabouts had higher numbers of HBIs due to this factor. The average marginal effect (see Table 6), shows that these roundabouts have higher numbers of HBIs by an average of 5.24 over a two-year period. Note that three arms in the fixed parameters model was found to be insignificant. The roundabouts that recorded higher number of HBIs with the three arm indicator were found either to have higher percentages of truck traffic, or they have three lanes (note that number of lanes for the whole roundabout is the average number of lanes at approaches and within the roundabout circulatory), or they are signalised.

Table 4
Percentage of HBIs and accidents recorded by position.

	Within 100 m of entry line	> 100 m from entry line	Within circulatory lanes
HBIs	75	12	13
Accidents	60	7	32
Truck Accidents	57	7	36

Circulatory lane width, was found to have, statistically, a highly significant effect in decreasing the number of HBIs (the t-statistic was significant at the 99% significance level (see Table 5)). A one metre increase in circulatory roadway width is associated with a decrease in the number of HBIs by an average of 14.87 (see Table 6). However this effect was found to be insignificant in the fixed parameters model. This effect of higher circulatory roadway width corresponds to the findings of Milton and Mannering (1998) and Miaou (1994) for road segments. They found that, in three-lane roads, other vehicles change their lanes less frequently in the presence of trucks and hence those roads become safer.

Table 5
Truck HBI Model Estimation Results.

Roundabout category	Variables	NB Random-parameters model		NB Fixed-parameters model	
		Coefficient	*t*-stat	coefficient	*t*-stat
Whole roundabout	**Constant**	−11.36	−4.80***	−8.40	−2.351**
	Geometric characteristics				
	Arm number (1 if 3 arm;0 otherwise)	0.064	0.224	0.284	0.662
	SD	*1.117*	*3.982****		
	Circulatory lane width (m)	−0.182	−2.912***	−0.178	−1.569
	Entry width (m)	0.213	2.937***	0.248	2.419**
	Traffic signal (1 if signal;0 otherwise)	−0.145	−0.492	0.215	0.395
	SD	*0.945*	*5.818****		
	Traffic signal (1 if un-signal;0 otherwise)	−0.017	−0.069	0.364	0.895
	SD	*0.842*	*4.574****		
	Traffic Characteristics				
	ln(AADT)	1.37	6.112***	1.08	3.440***
	Percentage AADTT	0.14	4.463***	0.110	1.618
	Dispersion parameter	1.81	5.448***	0.917	5.267***
	Observation numbers	70		70	
	Log-likelihood at constant only	−407.4612			
	Log-likelihood at convergence	−396.8231		−401.1357	
Within circulatory lanes	**Constant**	−10.87	−7.068***	−6.93	−1.108
	Geometric characteristics				
	ICD (m)	0.012	8.564***	0.006	1.198
	Circulatory lane width (m)	−0.266	−5.283***	−0.45	−3.302***
	Two-lane indicator	−1.86	−9.135***	−0.67	−0.847
	SD	*1.66*	*10.331****		
	Traffic signal (1 if un-signal;0 otherwise)	−1.51	−5.644***	−2.05	−2.652***
	Traffic signal (1 if signal;0 otherwise)	−0.082	−0.654	0.338	0.452
	SD	*1.153*	*13.072****		
	Traffic Characteristics				
	ln(AADT)	1.28	9.449***	1.16	1.702*
	Percentage AADTT	0.056	3.300***	0.21	2.626***
	Dispersion	18.95	2.118**	0.55	4.318***
	Observation numbers	70		70	
	Log-likelihood with constant only	−234.5069			
	Log-likelihood at convergence	−198.4219		−209.8665	
At Approaches	**Constant**	−13.36	−11.536***	−9.56	−5.458
	Geometric characteristics				
	Entry Width (m)	0.046	1.466	0.033	0.543
	SD	*0.026*	*4.650****		
	Traffic signal (1 if signal;0 otherwise)	0.41	2.952***	0.25	1.321
	SD	*0.357*	*4.473****		
	Lane number (1 if lane number = 2;0 otherwise)	−0.56	−4.103***	−0.36	−2.099**
	SD	*1.28*	*13.299****		
	Grade type (1 if grade separated; 0 otherwise)	−0.78	−5.366***	−0.52	−2.193**
	SD	*0.98*	*14.958****		
	Traffic Characteristics				
	ln(AADT)	1.60	12.674***	1.29	6.465***
	Percentage AADTT	0.16	8.387***	0.115	3.175***
	Dispersion parameter	1.33	9.643***	0.462	10.479***
	Observation numbers	284		284	
	Log-likelihood with constant only	−1154.866			
	Log-likelihood at convergence	−1093.753		−1111.236	

* At 90% significance level.
** At 95% significance level.
*** At 99% significance level.

Entry width was found to be a significant variable related to an increasing number of HBIs. A one meter increase in entry width is associated with an average increase of 17.5 HBIs over a two year period (by an average of 28.11 in the fixed parameters model). A possible reason behind this effect is that higher entry width is associated with higher traffic volume, as stated by Kimber (1980). In addition, higher entry width may make the driver feel that there is more space to overtake or pass the approach at a higher speed; as Arndt and Troutbeck (1998) stated, the speed of vehicles can be reduced by decreasing entry width, while Dingus et al. (2006) noted that event severity (accident, incident, and near-miss accidents) increases with increasing speed.

AADT and percentages of truck traffic were found to have a high impact on increasing the number of HBIs (*t*-statistic is significant at 99% confidence level). They were both found to have fixed effects across the observations, and Table 5 shows that the number of HBIs increases by 1.37% for a 1% increase in AADT, and Table 6 shows that a 1% increase in truck traffic increases the number of HBIs by an average of 11.47% over the two-year period studied.

The model predicts that signalisation leads to 56% of roundabouts having lower numbers of HBIs. From Table 6, the presence of signalisation decreases the number of HBIs by an average of 11.86. In contrast, signalised roundabouts were found to have an insignificant influence, in the NB fixed-parameters model. The signalised roundabouts that recorded higher harsh braking were found to be grade-separated with higher entry width relative to others.

The model predicts that 51% of the un-signalised roundabouts had a lower number of HBIs. Table 6 reveals that un-signalised roundabouts

Table 6
HBI Average Marginal Effects Results.

Roundabout category	Variable	NB Random parameters model	NB Fixed parameters model
Whole roundabout	Arm number (1 if 3 arm;0 otherwise)	5.24	32.1
	Circulatory lane width (m)	−14.87	−20.11
	Entry width (m)	17.47	28.11
	Traffic signal (1 if signal;0 otherwise)	−11.86	24.30
	Traffic signal (1 if un-signal;0 otherwise)	−1.42	41.11
	ln(AADT)	112.31	122.85
	Percentage AADTT	11.47	12.50
Within circulatory lanes	ICD (m)	0.03	0.04
	Circulatory lane width (m)	−0.54	−2.94
	Two-lane indicator	−3.75	−4.36
	Traffic signal (1 if un-signal;0 otherwise)	−3.1	−13.3
	Traffic signal (1 if signal;0 otherwise)	−0.17	2.18
	ln(AADT)	2.60	7.51
	Percentage AADTT	0.113	1.33
At approaches	Entry Width (m)	0.44	0.68
	Traffic signal (1 if signal;0 otherwise)	3.87	5.34
	Lane number (1 if lane number = 2;0 otherwise)	−5.30	−7.66
	Grade type (1 if grade separated; 0 otherwise)	−7.44	−10.97
	ln(AADT)	15.15	27.21
	Percentage AADTT	1.47	2.42

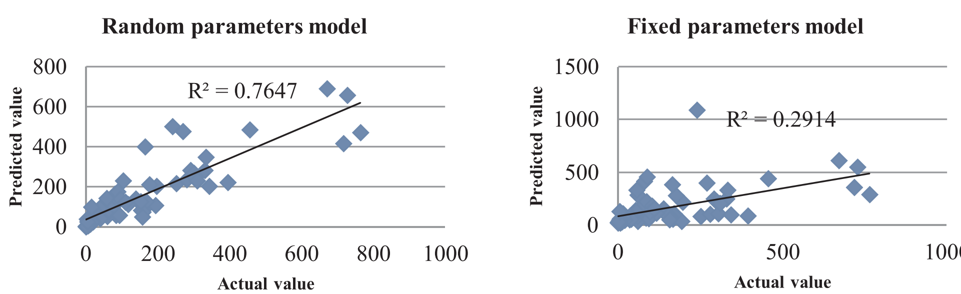

Fig. 4. Predicted Value and Actual Number of HBIs for Random- and Fixed-Parameters Negative Binomial Models for Whole Roundabouts.

are associated with lower numbers of HBIs by an average of 1.42 in the random-parameters model. In the NB fixed-parameters model, un-signalised roundabouts were found to have a statistically insignificant effect on HBIs. Eight of the locations that have a higher number of HBIs with the un-signalised indicator are at-grade roundabouts, they have high entry width, and high truck percentage and the majority of them have four arms. Note that in this study the roundabouts that are un-signalised have the lowest number of HBIs, while higher numbers of HBIs are recorded in signalised and partially signalised roundabouts. Signalisation is known to have an effect on driver behaviour. Inman et al. (2008) reported hard decelerations by a test truck at signalised intersections when the driver could not catch the green light. In addition Harbluk et al., 2007 states that 85% of hard braking occurred at signalised intersections. Thus, the reduction in HBIs observed by the current study at un-signalised roundabouts could be because traffic flows are less (meaning less potential traffic conflicts) or because drivers are not surprised by a traffic signal turning red.

The random parameter model predicts on average a lower number of HBIs at both signalised and un-signalised roundabouts. This implies that partially signalised roundabouts have higher counts of HBIs.

Within the circulatory lanes, all the variables illustrated in Table 3b except type of grade[4] were examined to find their effect on HBI occurrence. The following variables were found to have a significant fixed effect on HBIs:

- ICD,
- Circulatory roadway width,
- Un-signalised circulatory,
- AADT, and
- Percentage of truck traffic.

The influence of the following indicator variables on the occurrence of HBIs varied significantly across observations, because, statistically, the SD of the variable was found to be different from zero, which is indicated by the *t*-statistic (see Table 5):

- Two-lane circulatory, and
- Signalised circulatory.

Inscribed Circle Diameter (ICD) was found to be significantly related to an increase in the number of HBIs within the circulatory lanes (the *t*-statistic is significant at 99% significance level (see Table 5)). It was found that a 10 m increase in the ICD is associated with an increase in HBIs by an average of 0.3. Note that according to the reported marginal effect, the influence of ICD on HBIs is not high. The influence of the ICD was found to be insignificant in the fixed-parameters model.

It was found that reducing circulatory lane width by one metre was associated with a decrease in the number of HBIs by an average of 0.54, while in the NB fixed-parameters model the average was 2.94 (see Table 6). Note that according to the marginal effect, the influence of circulatory roadway width on HBIs was not high over the two-year period.

Un-signalised circulatory lanes are associated with lower HBIs, possibly for similar reasons as discussed earlier for whole roundabouts. As found in Table 5, circulatory lanes which are un-signalised,

[4] A correlation test between the independent variables found that at whole roundabouts and within the circulatory lanes, type of grade is highly correlated to inscribed circle diameter (with variation inflation factor (VIF) of > 5), therefore type of grade was excluded in the analysis for whole roundabouts and within the circulatory lanes.

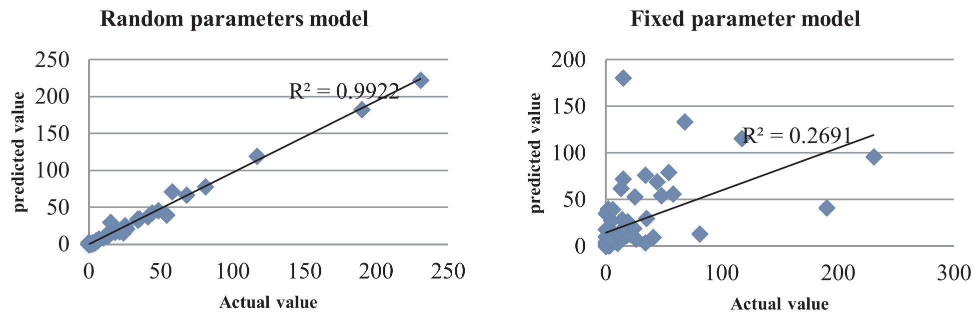

Fig. 5. Predicted Value and Actual Number of HBIs for Random- and Fixed-Parameters Negative Binomial Models within Circulatory Lanes.

statistically, have a highly significant fixed impact on decreasing the number of HBIs (the t-statistic is significant at the 99% significance level). Table 6 shows that the un-signalised circulatory is associated with a lower number of HBIs by an average of 3.1 (this contrasts with an average marginal effect of 13.3 in the fixed-parameters model).

As average annual daily traffic is expressed in a logarithmic form in the models, this implies that with a 1% increase in average annual daily traffic, the number of HBIs within the circulatory of the roundabouts increases by 1.28% (see Table 5). Table 6 shows that a 1% increase in percentage of truck traffic increases circulatory HBIs by an average of 0.113% over the two year period.

The two-lane indicator value was varied across the roundabout circulatory lanes having a normal distribution with a mean of −1.86 and a SD of 1.66, indicating that 87% of the circulatory sections with two lanes had lower numbers of HBIs than roundabouts with three lanes. Table 6 shows that two-lane circulatory lanes, are associated with a decrease in HBIs by an average of 3.75, while this effect was found to be insignificant in the fixed parameters model. The roundabouts that have a higher number of HBIs with two lane indicator were found to be grade-separated, and have high percentages of truck traffic. Note that within the circulatory lanes, AADT is lower in two-lane circulatory lanes compared to three-lanes, and this might be the reason for having lower HBIs in two-lanes, even though the percentage of truck traffic in two and three lane roundabouts is nearly the same.

Signalised circulatory lanes were found to have a random effect on occurrence of HBIs, in which 53% of the signalised circulatory lanes have a lower number of HBIs. Table 6 shows that HBI decreases by an average of 0.17 in the presence of signals within the circulatory lanes. There is no clear difference between the locations that have high and low HBIs with traffic signal presence, and the majority of them are grade-separated, and three-lanes, which appears to be the major cause for higher incidents in signalised circulatory lanes.

At approaches to the roundabouts, all the variables illustrated in Table 3c were examined to identify their influence on occurrence of HBIs. The following variables were found to have a significant fixed relationship to increasing the number of HBIs across the selected approaches:

- AADT at approaches, and
- Percentage of truck traffic at approaches

However, the influence of the following geometric variables was varied across the roundabout approaches resulting in random parameters:

- Entry width
- Signalised approaches
- Two lane approaches, and
- Grade separated indicator

Traffic related variables (AADT and percentage of truck traffic) were both found to have a high fixed effect on increasing the number of HBIs (as indicated by t-statistic in Table 5). As AADT increases by 1% the number of HBIs increases by 1.60%. A 1% increase in the percentage of truck traffic results in an average of 1.47% increase in the number of HBIs (the average marginal effect for the fixed-parameters model shows a 2.42% increase in the number of HBIs which is quite different from the random-parameters model).

Table 5 shows that the relationship to entry width varied across the approaches with a normal distribution having a mean of 0.046 and a SD of 0.026. Based on these distributions, 96% of the distribution is greater than zero (this indicates that for the majority of the roundabout approaches larger entry width corresponds to a higher number of HBIs). In the fixed-parameters model it was found that entry width had an insignificant effect on the number of HBIs. An increase in entry width of one metre corresponds to increases in the number of HBIs by an average of 0.44 over two years (see Table 6). As discussed earlier, entry width increases go hand-in-hand with the number of vehicles (as stated by Kimber,1980) and, in addition, increases in the speed of vehicles, and these changes make the approaches less safe (Arndt and Troutbeck, 1998).

Signalised approaches result in a random parameter, in which 87.5% of the approaches with presence of traffic signals have a higher number of HBIs. This shows that the effect of approach signalisation varies significantly across the roundabout approaches. Note that these indicators were found to have insignificant effect on HBIs in the fixed-

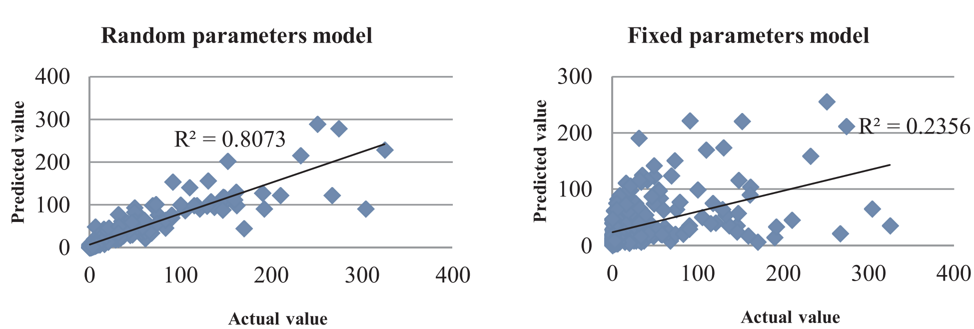

Fig. 6. Predicted Value and Actual Number of HBIs for Random- and Fixed-Parameters Negative Binomial Models at Approaches.

parameters model (as indicated by the t-statistic, see Table 5). Marginal effects in Table 6 reveal that the presence of signalised approaches is associated with higher HBIs by an average of 3.87. The approaches which recorded no increase in incidents with higher entry width have lower traffic volume, and the majority of them are located on A class roads, generally carrying medium traffic flows.

The two-lane indicator results in a random parameter, in which 67% of the approaches that are two lanes have a lower number of HBIs. The average marginal effect reveals that two lane approaches are associated with lower HBIs by an average of 5.30 over the two year period (in the fixed parameters model this was by an average of 7.66). The majority of the approaches that are two lanes and recorded lower incidents are located on A and B class (less trafficked) roads. The locations with the two lane indicator that have higher incidents have higher truck percentage. In contrast, Lee et al. (2007) have found that at intersections there is no relationship between HBIs and near-miss accidents with the number of traffic lanes, probably because their study includes all types of manoeuvres, not only HBIs. Also it was performed at other types of intersections only using linear regression models.

Grade type indicator results in a random parameters model, in which 78% of the approaches that are grade separated have lower numbers of HBIs. The average marginal effect reveals that approaches located on grade-separated roundabouts have lower HBIs by an average of 7.44 over the two year period (in the fixed parameters model this is by an average of 10.97). It was found that the majority of the approaches that recorded high number of incidents are signalised and they have high percentages of truck traffic.

6. Comparison of factors influencing total accidents and truck accidents with HBI model results

6.1. Overview

In order to explore the factors affecting total accidents, truck accidents and HBIs, total and truck accidents were related to the same traffic and geometric characteristics listed in Table 3a–c, using the random parameter negative binomial models. The results for total accidents are presented in Kamla et al. (2016), while the results for truck accidents are presented in Kamla et al. (2017). This will permit examination of whether HBIs are influenced by traffic and geometric variables in a similar way to total and truck accidents, so as to identify locations of high accident risk in the future supported by HBI data, which is the aim of this paper. The use of accident data over 11 years was chosen as a compromise, to generate a significant number of accident records while not being so long as to be unrepresentative of current circumstances and as illustrated in Fig. 1, the number of accidents is much smaller than the number of HBIs. Typically, road accident studies use data over shorter periods, for instance the studies included in the literature review include accidents over between three and seven years. A longer time period was chosen in this study so that accident risk could be assessed for all roundabouts, even so the number of truck accidents was zero for two of the roundabouts studied and only one accident for a further four roundabouts. This emphasises the problem with basing accident risk assessments on accident numbers alone. However, it does mean that the influence of other factors, such as modifications to the roundabouts and general trends in accident numbers, resulting from improvements in vehicle technology for instance, may confound the analysis. Indeed rates of serious injury accidents in the UK fell by about 20% over the years 2002 to 2012 (Department for Transport 2014).

According to STATS19 data, 4234 accidents occurred at the selected locations (entry, exit, and circulatory lanes) during the 11 years from 2002 to 2012. Of these, 26.6% of accidents included trucks. It was found that more fatalities occur in truck accidents (2.10% of accidents) than in accidents only involving other types of vehicle (1.7% of accidents). This compares to the 10,684 HBIs recorded at these locations during 2011–2012.

The relationship between the same traffic and geometric variables to the total accidents and truck accidents from the previous studies (Kamla et al., 2016, 2017) for the whole roundabouts, within circulatory lanes, and at roundabout approaches was computed using random-parameters models as described above for HBIs. In both studies the random-parameters models were compared to the fixed-parameters model, and it was found that random-parameters count data models provide better goodness of fit and more variables were found to be significant, giving a better prediction of events. For this reason, only the results from random-parameters models are shown in Table 7, comparing the results of the three studies.

6.2. Discussion of results

Regarding the relationship of traffic and geometric variables to accidents and HBI events as shown in Table 7, the following discussion is made:

6.2.1. Traffic variables

For whole roundabouts, and for approaches, an increase in traffic, expressed as ln AADT, leads to higher total accidents, and truck accidents, as expected from a wide range of previous studies (Maycock and Hall, 1984; Daniels et al., 2010; Šenk and Ambros, 2011; Rodegerdts et al., 2007; Guichet, 1997; Montella, 2007; Harper and Dunn, 2005; Turner et al., 2006; AASHTO, 2014). This relationship also holds true for HBIs. This is not the case for total and truck accidents on circulatory lanes alone; although the relationship does hold for HBIs (it may be that this is a case where the higher numbers of HBIs has led to traffic being identified as a significant variable where the lower number of total or truck accidents did not). However, the significance of the influence of AADT on increasing HBI numbers is small.

The percentage of truck traffic is also associated with higher total and truck accident and HBI numbers for whole roundabouts. This effect was found to vary across whole roundabouts when it is related to total accidents, those locations that were found to have lower accidents with higher truck percentage are only eight at-grade roundabouts.

The percentage of truck traffic is a significant variable for total and truck accidents and for HBIs within circulatory lanes. However, the percentage of truck traffic is not a significant variable for total accidents at approaches but remains so for truck accidents and HBIs. It appears from this analysis, therefore, that trucks have a greater impact on other vehicle accidents in circulatory lanes than at approaches.

6.2.2. Geometric variables

a) Inscribed circle diameter (ICD):
ICD, statistically, highly influences total accident, truck accident, and HBI numbers within circulatory lanes. This effect was found to be insignificant for HBIs at whole roundabouts, while statistically higher ICD was associated with a higher number of total and truck accidents at whole roundabouts. However, the marginal effect of 2 and 0.4 for total and truck accidents, respectively, indicates that its effect is small on total and truck accident numbers over the 11-year period and can be considered relatively unimportant.
b) Circulatory roadway width:
Higher circulatory roadway width results in fewer truck accidents and HBI numbers for the whole roundabouts and in circulatory lane models. This is not the case for total accidents.
c) Entry width:
At whole and at grade-separated roundabouts, a higher number of HBIs were recorded with higher entry width. However, this effect was found to be insignificant for total and truck accident numbers at whole roundabouts, but Retting (2006) states that roundabouts are less safe with higher entry width, and Kim and Choi, 2013 have found that total accident numbers increase with increasing entry

Table 7
Effect of an Increase in Geometric and Traffic Variables on Total Accidents, Truck Accidents, and HBIs using Random-Parameters Models.

Roundabout category	Variable	Total accident numbers	Truck accident numbers	HBI numbers
Whole roundabouts	ln(AADT)	↑↑	↑↑	↑↑
	Percentage of average annual daily truck traffic	86% ↑↑	↑↑	↑↑
	Un-signalised roundabouts compared to partially signalised roundabouts	↓↓	↓↓	51% ↓↓
	Signalised roundabouts compared to partially signalised roundabouts	–	76% ↓↓	48% ↓↓
	Two-lane roundabouts compared to three-lane roundabouts	–	66% ↓	–
	ICD	↑	↑	–
	Three-arm roundabouts compared to six-arm roundabouts	–	↓↓	48% ↓↓
	Circulatory roadway width	–	↓↓	↓↓
	Entry width	–	–	↑
Within circulatory lanes	ln(AADT)	–	–	↑
	Percentage of average annual daily truck traffic	↑↑	↑↑	↑↑
	Un-signalised roundabouts compared to partially signalised roundabouts	94% ↓↓	93% ↓↓	↓↓
	Signalised roundabouts compared to partially signalised roundabouts	–	–	53% ↓
	Two-lane roundabouts compared to three-lane roundabouts	–	–	87% ↓
	ICD	↑	↑	↑
	Circulatory roadway width	–	↓↓	↓↓
At approaches	ln(AADT)	↑↑	↑↑	↑↑
	Percentage of average annual daily truck traffic	–	↑↑	↑↑
	Signalised approaches compared to un-signalised approaches	↑	–	87% ↑
	Two-lane approaches compared to three-lane approaches	66% ↑	53% ↑	33% ↑
	Approaches located on grade-separated roundabouts relative to approaches located at at-grade roundabouts	99% ↑	↑	78% ↓
	Entry width	–	↑	96% ↑

The arrows show the increase or decrease in accidents or HBIs due to an increase in the variable and the number of arrows shows the strength of the relationship. Where a parameter is random, the % of the category influenced in the indicated direction is also given.

width. At approaches, more truck accidents and HBIs were recorded with higher entry width, while this was not the case for total accident numbers, yet the marginal effect for HBIs (0.44) and truck accidents (0.081) is low and is considered relatively unimportant.

d) Signalisation:
The majority of the signalised whole roundabouts have lower truck accident numbers and half of them also have fewer HBI numbers. On the other hand, the signalised indicator was found, statistically, to be insignificantly related to total accident numbers at whole roundabouts.
Half of the signalised circulatory lanes have lower numbers of HBIs, while this was not so for total and truck accident numbers. However, the average marginal effect for HBIs (−0.17) was low over the two-year period and is considered relatively unimportant. The majority of signalised approaches have more total accidents and more HBIs (although this is not the case for truck accidents). Nevertheless, the values of the marginal effect for total accidents (1.81) and HBIs (3.87) were found to be small and are considered relatively unimportant.
Almost all un-signalised circulatory lanes are associated with fewer numbers of total accidents, truck accidents, and HBIs. The lower number of these events is probably due to lower AADT in un-signalised roundabouts compared to signalised and partially signalised roundabouts.

e) Number of lanes:
The majority of whole roundabouts have lower numbers of truck accidents when approaches are two-lane, while this was not the case for total accident and HBI numbers. However, according to the marginal effect of −1.88 over the 11-year period for truck accidents, this effect can be considered relatively unimportant.
For the circulatory lanes, the two-lane approach indicator was found to be unrelated to the numbers of total and truck accidents. The majority of circulatory lanes that are two-lane have fewer HBI numbers, but the marginal effect of −3.75 over two-years, is low and can be considered relatively unimportant.
The majority, about half and a third of two-lane approaches have greater numbers of total accidents, truck accidents, and HBIs, respectively, than three-lane approaches.

f) Grade type indicator at approaches:
The majority of approaches that are located at grade-separated roundabouts have higher total accident and truck accident numbers, while the majority of them are associated with fewer HBIs. Approaches that are located on grade-separated roundabouts constitute 117A- and B- class roads and 94M-class roads and there are a high number of HBIs in A-class approaches. This is not the case for total and truck accidents because all approaches that are located at grade-separated roundabouts (A- and M-class approaches) are associated with high numbers of total and truck accidents.

g) Number of arms:
Three-arm roundabouts were found to have fewer truck accidents and fewer HBIs, respectively, when considering whole roundabout events. However, this effect was found to be insignificant on total accidents at whole roundabouts, even though previous studies (Kennedy, 2007; Brüde and Larsson, 2000) have found that three-arm roundabouts are associated with lower rates of total accidents.

7. Summary and discussion

The random-parameters models for HBIs are better than the fixed-parameters models. This agrees with previous studies for total and truck accidents at the same roundabouts (Kamla et al., 2016, 2017). It was found that the HBI random-parameters model is significant at 97% for whole roundabouts and at more than 99% for approaches and within circulatory lanes, and more variables were found that randomly affect the incidents of harsh braking, which were not significant in the fixed-parameters models. Thus, the predicted HBI numbers provide more reliable predictions of the actual HBI numbers when using the random-parameters models compared to use of the fixed-parameters models. The effect of some parameters on HBIs, total and truck accidents varies significantly across observations, while some remain fixed across observations, as summarised in Table 7.

The most important variables were AADT and percentage of truck traffic, which were found to have a positive influence on both accidents and HBIs. Regarding the geometric variables, while there are differences between the models, signalisation, circulatory roadway width, number of arms, and the two-lane indicator are considered the most important factors influencing both accidents and HBIs. The number of common variables in the models is higher for truck accidents and HBIs models than for total accidents and HBIs models. This might be explained by the fact that the HBIs are solely for trucks. The similarity between the models may be influenced by the fact that they cover different time periods, which is comparatively long for the accident numbers, compared to other studies.

HBIs provide a much larger data set than accidents. Therefore, in as far as they can provide a surrogate for accident numbers, they present the opportunity for modelling of accident risk in a much shorter time period than for accidents. This may be important as accident rates fall and vehicle technology continues to develop. It is important to note that the HBI results studied here are only for a small part of the truck fleet, which may not be representative of the entire fleet in terms of vehicle type, driver behaviour or geographical coverage. Any relationship between HBIs and accident risk is likely to be complex and the extent to which any individual HBI represents a manoeuvre that could be regarded as a high-risk incident or near-miss accident could not be studied taking the approach described in this paper. The HBIs are recorded at a single level of deceleration for each vehicle and other important factors, such as truck load, or environmental conditions were not considered. However, other vehicle sensors can provide some information about these factors, for instance from accelerations, engine demand, the use of windscreen wipers or whether the truck lights are on. Further work considering a fuller range of information from vehicle sensor records may reveal a more detailed relationship with accidents.

The opportunity to exploit this type of data will grow as data for more trucks and other vehicles becomes available, as sensor technology develops and becomes more common, for instance with the introduction of autonomous vehicles. Further work will look at longer term trends in HBI numbers and may reveal changes in safety risk. It will be interesting to compare the rankings of roundabouts with respect to accident risk and HBIs to further consider the relationships between them. It is also intended to extend the research beyond roundabouts to other intersections and road geometries and to include road surface conditions as variables in the models. In addition, other vehicle manoeuvres such as harsh cornering or high speed are recorded as events in the data record and should be considered as possible indicators of accident risk, individually or in combination with harsh braking.

8. Conclusions

In conclusion, the random-parameters models were found to be better models for HBIs and accidents relative to the fixed-parameters models. When HBI models are compared to those for total and truck accidents, it was found that HBIs and their positions are influenced by traffic and geometric variables in a similar way to total and truck accidents. Therefore, is important to consider their ability to identify locations of high accident risk. There are limitations to this study, concerning the time periods over which data was sampled and the possibility of characterising accident risk from a simple record of harsh braking. However, it is concluded that HBI records can be used to support accident modelling, they are a source of much more numerous data than accidents, and this may be important in considering changes or trends in accident risk over a much shorter time than for accident studies. Further studies, including other truck sensor data, may help further in characterising accident risk in the future.

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