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Central European comparative study of traffic safety on roundabouts

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Abstract

Roundabout is a popular and safe type of road intersection, which has become widely used around the world, including Central European countries. To conduct statistical comparative study of traffic safety on roundabouts, accident prediction models (safety performance functions) have to be developed. With this aim accident, traffic and geometry data for samples of rural roundabouts in four Central European countries (Czech Republic, Hungary, Poland, Slovakia) were collected and used in statistical modelling, using state-of-the-art generalized linear modelling framework. Both individual and combined models were developed, which enabled insight into relationships between explanatory variables and accidents, as well as comparison with models from international studies. In the end study limitations are summarized and further improvements outlined.

Keywords: Traffic safety; roundabout; accident prediction model; Central Europe

1. Introduction

Roundabout is a popular and safe type of road intersection, which has become widely used around the world. The safety benefit of roundabout conversions has been recognized world-wide (Persaud et al., 2001, Elvik, 2003). Although in the past two decades roundabouts have also been built in Central European countries (Michalski et al., 2000; Hóz, 2004; Slabý, 2005; Škoda, 2007), their safety impact has not been properly evaluated. Lack of relevant data and experience is usually the reason, since developing necessary statistical tools (accident prediction models or safety performance functions) is not easy and straightforward task. Applying the models developed in other parts of the world is also an option, however several biases may occur, due to differences given by different design guidelines as well as driving behaviour.

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This situation motivated us to develop safety performance functions of typical roundabouts in four Central European countries (Czech Republic, Hungary, Poland, Slovakia). To this end, homogeneous samples of typical roundabouts in each country were used. Accident frequencies and other safety-related data were collected and used in statistical modelling, using state-of-the-art generalized linear models with negative binomial error structure.

2. Data and methods

2.1. Sample

The idea was to collate sample of the roundabouts in the most typical settings. In the Czech Republic, such conditions are: unsignalized roundabouts, located on urban roads, with 4 legs and single lane (Novák and Ambros, 2012). This specification generally applies also in other countries. The first collection therefore focused on these settings.

However the crucial point is that for accident prediction models development, traffic volume data are necessary. These usually come from traffic census, which mostly focus on core road network, rather than urban and local roads. Due to this fact we found that traffic data are not available for most urban roundabouts.

Therefore in the second round we decided to collect data on rural roundabouts, which are more likely to be included in traffic census networks. This way 72 roundabouts were selected (13 in the Czech Republic, 21 in Hungary, 29 in Poland, 9 in Slovakia, see Fig. 1). The selection included both rural roundabouts and suburban roundabouts (located at city entrances). We made sure that the samples involved typical roundabouts, i.e. with approximately perpendicular legs and without bypasses.

Fig. 1. Localization of the studied roundabouts across the four countries (Czech Republic, Hungary, Poland, Slovakia) in Google Maps.

2.2. Variables

At roundabouts data on various risk factors may be collected:

- According to a French standard (SETRA, 2002) the deflection of vehicle paths through a roundabout is a major safety factor.
- In a study of Hels and Orozova-Bekkevold (2007), among others diameter of central island and circulatory roadway width were used.
- International comparison of roundabout design guidelines (Kennedy, 2007) concluded that the main roundabout safety determinant is a combination of entry deflection and entry width.
- In the United States, Rodegerdts et al. (2010) found that entry radius, entry width, approach half width, inscribed circle diameter and circulating width were positively correlated with accidents.
- Daniels et al. (2011) used various explanatory variables, including presence of traversable apron, central island diameter, inscribed circle diameter and road width on the roundabout.
- In Czech roundabout accident prediction models, width of traversable apron and deviation angle were significant predictors (Šenk and Ambros, 2011; Ambros and Slabý, 2013).
- At Danish roundabouts, the height of central islands, sight distances, pavement markings and signage have a safety effect (Jensen, 2015).

This overview shows, among others, the importance of deflection, i.e. amount of trajectory changes imposed by roundabout geometry. However different terminology and definitions were found in international design guidelines. For the purpose of current analysis, following terminology was adopted:

- Entry angle (α) is a measure of trajectory change on roundabout entries.
- Deviation angle (ω) measures a deflection of trajectory between two opposing roundabout legs.

Illustration is provided in Fig. 2. Using online map sources, both entry and deviation angles were collected for all four trajectories on each roundabout. For analysis, average values were used. Final selection included 12 following variables:

- Accident frequency in 5 years (2009 – 2013), categorized into property-damage-only accidents (PDO), injury accidents and total accidents (N_{pdo}, N_{inj}, N_{tot})
- Traffic volume, as total number of entering vehicles per day (I).
- Inscribed circle diameter (“roundabout diameter”, D) and central island diameter (D_{isl}).
- Average width on entering and exiting legs, circulating width and width of traversable apron (W_{entry}, W_{exit}, W_{circ}, W_{apron}).
- Average entry and deviation angles (α, ω).
- Presence of pedestrian crossing (or cycle path) on roundabout legs (PED).

Accident data were retrieved from Traffic Police in each country. PDO accident data were available only in the Czech Republic and Slovakia, where they made up 64% and 75% of all the accidents in both samples, respectively. In Hungary and Poland PDO counts were not available.

Traffic volumes were obtained from the results of national traffic census in each respective country. Other variables (geometrical parameters) were collected using online map sources. Descriptive characteristics of the variables are summarized in Table 1.

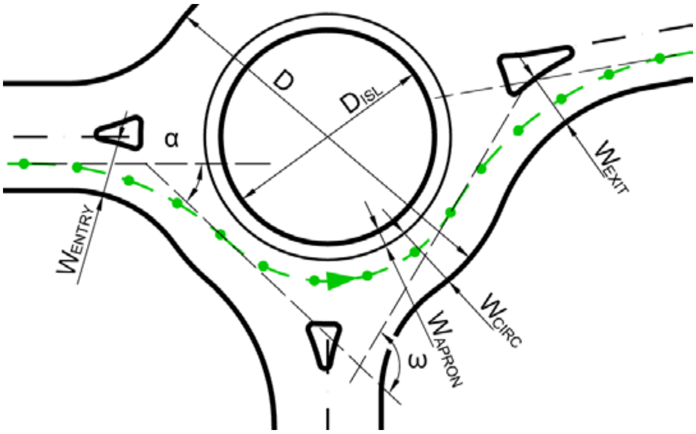

Fig. 2. Definition of roundabout geometry design parameters (diameters, widths, angles), related to driving trajectory (in green).

Table 1. Descriptive characteristics of response and explanatory variables for the four countries.

Variable [unit]	Min / max / mean / std. dev. or percentages			
	Czech Republic (CZ)	Hungary (HU)	Poland (PL)	Slovakia (SK)
N_{pdo}	0 / 17 / 4.69 / 4.47	N/A	N/A	0 / 3 / 1.00 / 1.00
N_{inj}	0 / 5 / 1.53 / 1.50	0 / 6 / 1.09 / 1.41	0 / 3 / 0.51 / 0.78	0 / 2 / 0.55 / 0.72
N_{tot}	0 / 20 / 6.23 / 5.46	0 / 6 / 1.14 / 1.38	0 / 3 / 0.65 / 0.89	1 / 3 / 1.55 / 0.72
I [veh/day]	5225 / 36600 / 12692.76 / 8408.86	8435 / 42385 / 23052.13 / 9149.74	3607 / 33859 / 12294.51 / 6970.07	4457 / 43022 / 17110.55 / 12498.52
D [m]	24 / 43 / 34.38 / 5.70	38 / 78 / 58.28 / 11.69	32 / 45 / 38.32 / 3.82	29 / 56 / 39.33 / 7.87
D_{isl} [m]	8 / 26 / 16.84 / 5.75	22 / 63 / 39.52 / 12.36	17 / 30 / 24.00 / 4.05	12 / 40 / 22.44 / 8.33
W_{entry} [m]	4.0 / 6.0 / 4.50 / 0.58	4.0 / 7.0 / 5.14 / 0.72	3.5 / 6.0 / 4.03 / 0.60	5.0 / 7.0 / 5.66 / 0.70
W_{exit} [m]	4.0 / 6.0 / 4.61 / 0.59	4.0 / 7.0 / 5.90 / 0.76	3.5 / 6.5 / 4.57 / 0.63	6.0 / 7.0 / 6.33 / 0.50
W_{circ} [m]	5.0 / 9.5 / 6.61 / 1.29	7.0 / 9.0 / 8.00 / 0.63	3.5 / 7.0 / 4.94 / 0.79	6.0 / 9.0 / 7.11 / 1.26
W_{apron} [m]	0.0 / 4.0 / 2.15 / 0.89	0.0 / 4.0 / 1.38 / 1.31	1.5 / 3.5 / 2.21 / 0.50	0.0 / 2.5 / 1.33 / 1.03
α [°]	16.75 / 49.00 / 33.21 / 9.08	16.00 / 112.00 / 24.26 / 4.34	24.75 / 107.00 / 34.43 / 6.08	13.75 / 27.75 / 20.58 / 5.39
ω [°]	34.50 / 89.25 / 58.89 / 16.54	55.75 / 82.25 / 69.70 / 7.78	59.00 / 89.75 / 75.41 / 8.52	39.50 / 78.00 / 60.31 / 12.07
PED (0 … absent 1 … present)	0: 53.8%; 1: 46.2%	0: 81.0%; 1: 19.0%	0: 13.8%; 1: 86.2%	0: 55.6%; 1: 44.4%

Consistently with state-of-the-art, following form of accident prediction model was adopted:

$$P = \beta_0 \cdot I^{\beta_1} \cdot \exp(\beta_2 x_2 + \beta_3 x_3 + \cdots) \qquad (1)$$

where expected (predicted) accident frequency P is estimated through multiplicative regression model, including explanatory variables of exposure (traffic volume) I and other risk factors x_i; β_i are regression coefficients to be estimated in modelling (Ambros and Slabý, 2013; Ondrejka and Machciník, 2013; Borsos et al., 2014; Gaca and Kieć, 2015).

Regression models were developed in IBM SPSS. Candidate models were tested with all accident severity categories as response variables. All explanatory variables were entered and sequentially removed, using backward elimination, in order to achieve their statistical significance at minimum 10% level.

3. Results

3.1. Individual models

We were able to develop individual models for the Czech Republic, Poland and Slovakia; however none could be developed for Hungary. Table 2 summarizes successful combinations of response variable and explanatory variables.

Table 2. Overview of variables used in the accident prediction models.

	Response variables			Explanatory variables								
	N_{pdo}	N_{inj}	N_{tot}	I	D	D_{isl}	W_{entry}	W_{exit}	W_{circ}	W_{apr}	$DEFL$	PED
CZ	▨			▨	▨							
PL		▨		▨			▨		▨			
SK	▨	▨		▨								

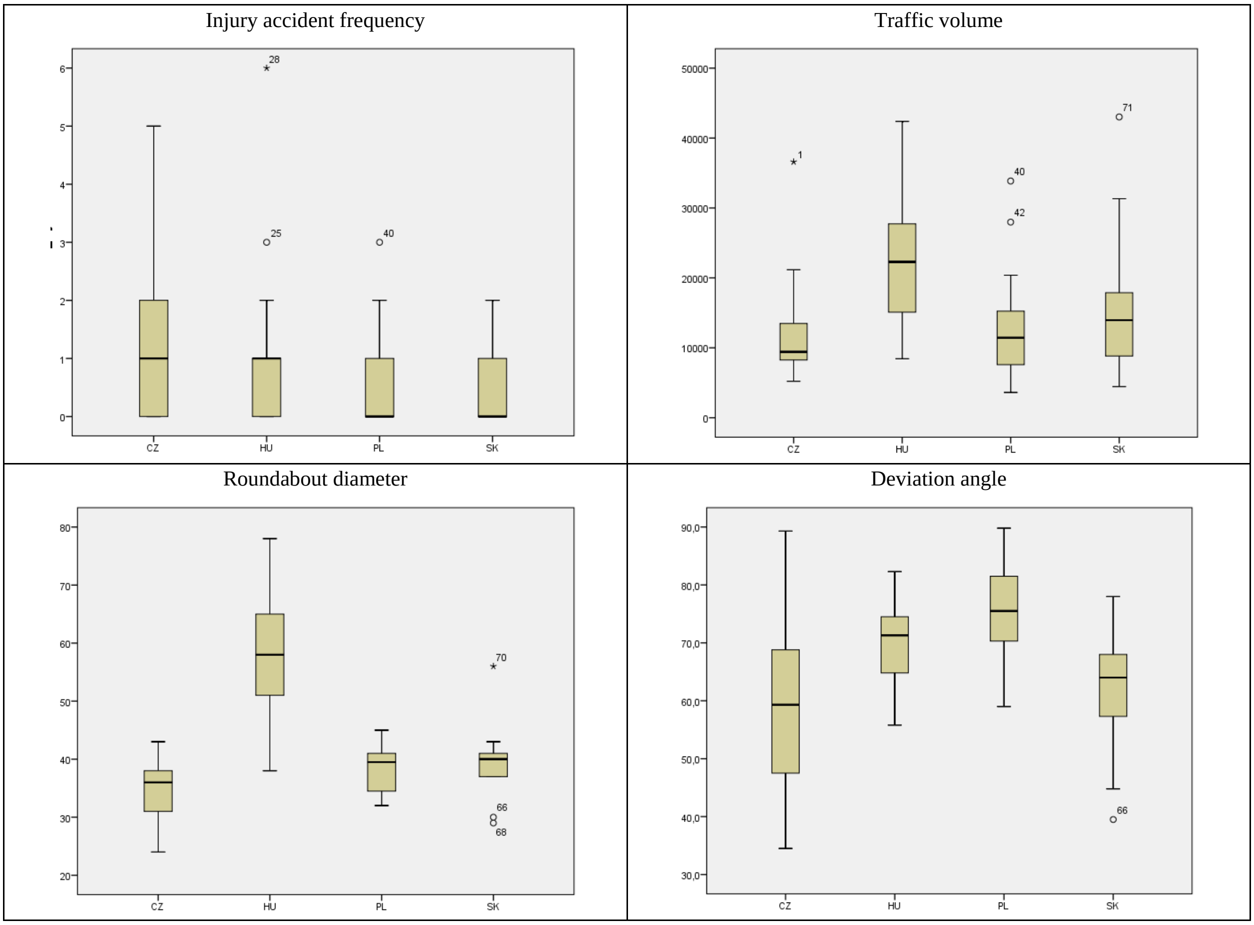
Injury accident frequency
Traffic volume
Roundabout diameter
Deviation angle

Fig. 3. Illustration of overlapping ranges of selected variables (injury accident frequency, traffic volume, roundabout diameter, deviation angle) between the four countries (CZ, HU, PL, SK).

Regression coefficient signs reveal the directions of statistical associations between predictors and response variables. The developed models had following relationships:

- Traffic volume (I) had always positive relationship, i.e. it is associated with accident increase, as generally expected.
- Roundabout diameter (D) had negative relationship, i.e. the larger diameter, the lower accident frequency.
- Entry width (W_{entry}) was associated width accident increase, while the opposite was found for circulating width (W_{circ}).

However it is evident that most of explanatory variables did not contribute to any models. Nevertheless such finding is not unique: for example Daniels et al. (2011) found that only 1 out of 11 geometrical variables was significant in final model.

In order to look for further statistical relationships, we took an additional step. When inspecting distributions of values of various variables, we found they are to some extent similar – see Fig. 3 for example box plots of variables N_{inj}, I, D, ω across the four countries (CZ, HU, PL, SK). Some features are not completely comparable: for example Hungarian roundabouts seem to have higher traffic volumes, as well as diameters. Nevertheless the variable ranges are at least partially overlapping. This fact may be interpreted not only as similar safety and traffic conditions in the studied countries, but also partial similarity of guidelines, which dictate roundabout geometry. Based on this idea, we attempted to develop a model with data combined from all 4 samples (72 roundabouts).

3.2. Combined model

Two variants of combined model were developed, including following explanatory variables: traffic volume (I), apron width (W_{apron}) and deflection (α, ω). In the following text, model equations for injury accident frequency (N_{inj}) are reported. Annual values were obtained from original (five-year) after dividing intercept by five.

- Model with entry angle:

$$N_{inj}\ (1\ year) = 0.004 \cdot I^{0.424} \cdot exp(0.369 \cdot W_{apron}) \cdot exp(-0.034 \cdot \alpha) \tag{2}$$

- Model with deviation angle:

$$N_{inj}\ (1\ year) = 0.001 \cdot I^{0.639} \cdot exp(0.402 \cdot W_{apron}) \cdot exp(-0.031 \cdot \omega) \tag{3}$$

Relationship directions, given by the regression coefficient signs, are following:

- the higher traffic volume, the higher accident frequency
- the wider apron width, the higher accident frequency
- the higher deflections, the lower accident frequency

The first and the third findings are logical – traffic volumes are the main risk factor, while deflection contributes to lower speed and thus has a protective effect. On the other hand, the finding related to apron is not completely clear – in a previous study (Šenk and Ambros, 2011), apron width was negatively associated with accident frequency. However Jensen (2015) report that at Danish single-lane roundabouts “as the truck apron gets wider the safety effects get worse”, which is consistent with our finding. The explanation may be the wider the apron, the narrower the central island, which provides more space and visibility, leading to increase of speeds and lower safety.

In order to compare the models with other equations from the world, simple model (safety performance function) was further developed from the same dataset, using only traffic volume as an explanatory variable:

$$N_{inj}\ (1\ year) = 0.002 \cdot I^{0.458} \tag{4}$$

Literature was searched for models with comparable coefficient values. Two models were found: from United States (Rodegerdts et al., 2010, Exhibit 5-20) and New Zealand (NZTA, in press, Table 19). New Zealand model was developed on approach-level, therefore its intercept was multiplied by 4 in order to obtain total sum for 4-leg roundabouts. Model coefficients are reported in Table 3.

Table 3. Comparison of regression coefficients between safety performance functions.

	$N = \beta_0 \cdot I^{\beta_1}$	
	β_0	β_1
This study	$2.16 \cdot 10^{-3}$	0.458
United States (Rodegerdts et al., 2010)	$1.3 \cdot 10^{-3}$	0.5923
New Zealand (NZTA, in press)	$1.73 \cdot 10^{-3}$	0.53

The model graphs (safety performance functions) are visualized in Fig. 4. The graphs present values of annual accident frequencies, depending on traffic volume. The curve in bold is based on equation 4 (labelled as "CE" – Central Europe), the other two curves (for American and New Zealand trends, labelled "USA" and "NZ") were derived using regression coefficients from Table 3.

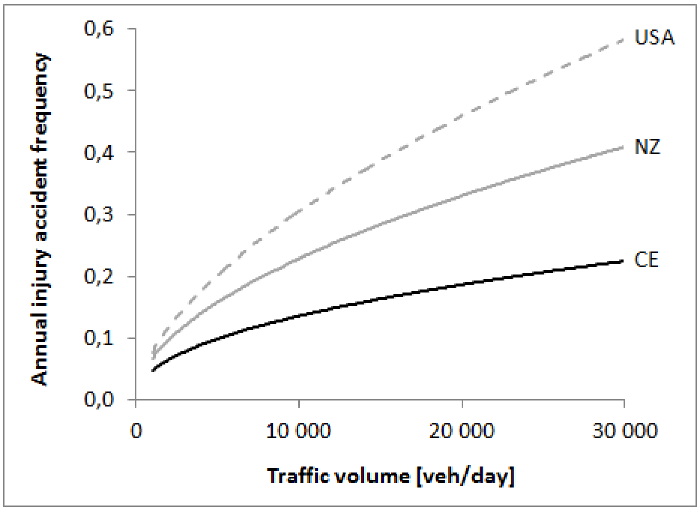

Fig. 4. Comparison of safety performance functions from this study ("CE", in bold) with international models from USA and New Zealand ("NZ").

4. Discussion and conclusions

The study aimed to develop accident prediction models (safety performance functions), which are necessary for statistical safety evaluation of roundabouts. Accident, traffic and geometry data were collected for samples of rural roundabouts in four Central European countries (Czech Republic, Hungary, Poland, Slovakia).

Since most of explanatory variables were not significant, it was attempted to develop model based on combined sample. According to this final model, injury accident frequency is positively associated with effect of traffic volume and apron width, while negatively associated to deflection (in terms of both entry and deviation angles). These findings were found consistent with previous studies. Validity is also confirmed by the fact that coefficients of simple (exposure-only) model are partially comparable to other studies (see Table 3 and Fig. 4).

Nevertheless it has to be noted there are some limitations to the presented study and developed statistical relationships:

- *Sample size*: It is evident that size of individual national samples is relatively small. Typical minimal recommended sample size is 30 units: Polish sample suffices this requirement, but the others do not. As mentioned, basic limitation was availability of traffic volume data.

- *Uncertainty in response variable*: At roundabouts, very rarely severe injuries occur. For adequate description of safety level it would be thus beneficial to use total accident counts, including also property-damage-only (PDO) accidents. However reporting rates are generally low with decreasing severity. For example according to ETSC (2007), only 61% and 69% of slight injuries are reported in the Czech Republic and Hungary, respectively. In many countries (including Poland and Slovakia) underreporting studies have not been conducted, and true reporting rates are therefore unknown. Regarding PDO accidents, their general reporting rate was estimated as low as 25% (Elvik et al., 2009). In addition some countries, including Hungary, do not report PDO accidents at all (ETSC, 2006). Response variables, based on roundabout accident counts, are thus relatively uncertain.
- *Incomplete explanatory variables*: In regression accident modelling, various sources of bias may occur, including omitted variable bias (Elvik, 2011). Selected explanatory variables are by no means complete – one can for example imagine vehicle speeds or sight conditions, which are very likely to influence roundabout safety, however their data collection is not straightforward. There are also other geometrical parameters to be collected, such as angles between roundabout legs or parameters of approaching legs.
- *International comparison*: It is tempting to derive conclusions based on curves in Fig. 4. However samples are likely to be incomparable. One difference may be in speed: NZ model is reported as applicable for 80 km/h roads, while CE sample may have lower speeds, since it includes also suburban roundabouts. In addition CE sample is from rural roundabouts, while USA source does not provide relevant details; however studies dealing with roundabouts safety traditionally focus rather on urban areas (Hydén and Várhelyi, 2000; Montella, 2011; Pokorný, 2011; Sacchi et al., 2011; Ambros and Janoška, 2015), which dictates also modelling results. Accident reporting rates in individual countries are also different. For further issues related to comparing international accident prediction models see Turner et al. (2011).

To conclude, the main finding is that collected data are relatively comparable (Fig. 3) and may thus be used for combined model. We suppose that this model is valid and it shows the importance of deflection. This fact has often not been adequately considered: for example Czech guidelines acknowledge the role of deflection, but do not state any explicit guidance. In Italian standard, a threshold for deviation angle is set, but without taking into account other related parameters the main parameters used by the international standards, such as radius of deflection and entry path radius (Montella, 2013).

Further studies may focus on overcoming the above mentioned limitations. Sample sizes should be larger and surrogate safety measures (such as traffic conflicts) could be used in order to improve safety level quantification. Speed surveys would also be beneficial, since speed provides a link between roundabout safety and geometry. In addition direct observation and geometrical parameter measurement would help, and may lead to collection of other variables related to driving behavior, which were currently not considered.

Roundabouts are acknowledged as beneficial countermeasure, which has contributed to traffic safety improvement in Central European countries (Eksler et al., 2005). However motorization and behavior, as well as road infrastructure, is gradually changing. In this context it is hoped that the research efforts, presented in this paper, will provide updated findings, which may be translated into future editions of roundabout design guidelines.

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