HOW DO ROUNDABOUT ENTRY DESIGN PARAMETERS INFLUENCE SAFETY?

Jan Novák (Corresponding author)
CDV – Transport Research Centre
Líšeňská 33a, 636 00 Brno, Czech Republic
Tel. +420 541 641 224; Fax +420 541 641 712; E-mail jan.novak@cdv.cz

Jiří Ambros, PhD
CDV – Transport Research Centre
Líšeňská 33a, 636 00 Brno, Czech Republic
Tel. +420 541 641 362; E-mail jiri.ambros@cdv.cz

Jindřich Frič, PhD
CDV – Transport Research Centre
Líšeňská 33a, 636 00 Brno, Czech Republic
Phone +420 541 641 716; E-mail jindrich.fric@cdv.cz

Submitted for presentation at the 97th Annual Meeting of the Transportation Research Board, January 7–11, 2018.

Submitted: July 30, 2017

Revised: November 14, 2017

Total number of words: 5,748 (abstract, text, references) + 7 figures/tables × 250 = 7,498

ABSTRACT

Roundabout is considered the safest intersection design; however, its safety effect may not be satisfactory at each specific roundabout. This is true especially in countries where roundabout design is a relatively new concept, such as in the Czech Republic. Specifically, most Czech roundabout crashes were found to occur on entries. This motivated the presented study to answer the question, how do entry design parameters influence safety on Czech roundabouts, and if possible, use the findings to update current Czech roundabout design guidelines. To this end, the study comprised three analyses: crash-based safety performance functions, speed analysis, and finally safety performance functions which incorporated speed. All three analyses proved that entry design parameters have a statistically significant influence on safety, in terms of crash frequency, severity and speeds. Given the study objective, this fact should be considered in Czech roundabout design guidelines.

INTRODUCTION

Intersections, where road users may change their directions in order to get to their destinations, are crucial for the road network operation. However, they also present a discontinuity in the road network and, therefore, a potential hazard, due to a number of conflict points and traffic complexity (*1 – 4*). In the United States, more than 50% of fatal and injury crashes take place at or near intersections (*5*). In Europe, every 5th road fatality is due to intersection crashes (*6*). In this context, roundabout is considered the safest intersection design, as it introduces few conflict points and low speeds, which are associated with reduction of number and severity of crashes (*7*). Nevertheless, the safety improvements may not produce satisfactory results at each specific roundabout (*8*); in addition, the crash reductions are most pronounced for motor vehicles and less pronounced for pedestrians or bicyclists (*9*). Other roundabout disadvantages comprise for example difficulties for visually impaired users, or potential increase of single-vehicle and fixed-object crashes (*10*).

One of explanations, offered by Montella (*11*), is that there may be safety issues especially in countries where roundabout design is a relatively new concept. The Czech Republic, where roundabouts have emerged since early 2000s, may be one of such examples. In fact, Czech roundabout safety performance was found inferior, compared to other European countries (*12*), which may be due to insufficient roundabout experience, both in terms of design practice and driving performance. Similarly to other countries (*9*), most Czech roundabout crashes occur on entries: entering-circulating crashes present 58% of all roundabout crashes (*13*), probably due to failure to give way (*14*).

Given these facts, the presented study aimed to answer the question, how do entry design parameters influence safety on Czech roundabouts? Driving behavior on roundabout entries is likely to be influenced by driving path geometry, sight conditions, etc.; however, their impact has not been specifically quantified. The objective was to investigate the relationships between entry design parameters and safety, and if possible, use the findings to update current Czech roundabout design guidelines.

BACKGROUND

International perception of superior roundabout safety performance comes mostly from studies of crash reductions after converting traditional intersections to roundabouts. For example, a study of 23 conversions in the US (*15*) found 40% reduction of all crashes, 80% of injury crashes, and 90% of fatal crashes. Meta-analysis of 28 studies outside of the US (*16*) showed 30% to 50% reduction in the number of injury crashes; fatal crashes were reduced by 50% to 70%. A Czech before-after study (*12*) identified approx. 50% reduction of both total and injury crashes. And recent meta-regression analysis (*17*), based on 44 international studies, concluded that converting intersections to roundabouts is associated with a reduction of fatal and injury crashes of about 65% and 40%, respectively.

However, roundabout implementations may be influenced by other considerations, such as capacity requirements or spatial constraints; as a result, final performance may not be as safe as expected. When studying roundabout crash types, the highest percentage usually relates to roundabout entries. In a US study, entering-circulating crashes were found to represent about three quarters of all collisions (*18*); above-average numbers were also identified in samples from the United Kingdom (*19*: up to 71%) and Switzerland (*8*: 57%).

In terms of roundabout geometry, scientific literature provides indications of several safety-relevant characteristics. Some of them are as follows (sorted chronologically):

- UK study of 4-leg roundabouts (*19*) reported several safety-related geometric variables, including entry path curvature, entry path radius (the inverse of entry path curvature) and entry width.
- According to German experience (*20*), sufficiently large Δ parameter (defined as the distance between the straightest line from an entry to the opposite exit and the shortest track a driver could take on the circulating roadway) is the precondition to necessary speed reduction. Similar concept was referred to as "lateral displacement" (*21*) or "lateral deflection" (*22*).
- Approach curvature, central island diameter, separation between legs and other factors were found influential in an Australian study (*23*).
- Swiss research (*8*) found correlation between smaller deviation angles and higher crash rates, caused by failing to give way and increased through-speeds.
- International comparison of roundabout design guidelines (*24*) concluded that the main roundabout safety determinant is a combination of entry deflection and entry width.
- A detailed study of roundabout crash contributory factors (*14*) stressed the crucial role of a moderate radius of deflection and a large deviation angle.

In principle, most all the mentioned parameters are related to deflection, either on entries (entry angle, i.e., the conflict angle between the entering and the circulating traffic) or in the roundabout center (deviation angle, i.e., the amount of trajectory change imposed by central island). According to Rodegerdts et al. (*7*), reducing the vehicle path radius at the entry (i.e., deflecting the vehicle path) decreases the relative speed between entering and circulating vehicles and thus results in lower entering-circulating vehicle crash rates. These facts have been reflected in several guidelines and standards, for example:

- Spanish standards (*25*) set range of entry angle values 20° – 60° (ideally 30°); the same range is required by UK *Design Manual for Roads and Bridges* (*26*).
- Swiss and Italian standards require a deviation angle above 45° (*27*, *28*).

Regarding safety requirements, Czech guidelines recommend verification of through-speeds; however, they do not present any specific values of entry angle or deviation angle. This study aims to fill this gap by investigating the relationships between entry design parameters and safety, and using the findings to update current Czech roundabout design guidelines.

To this end, the study comprised three analyses, which are described in the following text.

ANALYSES

Sound research might provide meaningful insight to improve geometric design standards and guide towards the optimal balance between the conflicting design parameters (*28*). In order to take into account the multi-factor character of the issue, the first step is a multivariate analysis, which considers simultaneously the effects of many factors on the incidence of crashes (*29*). Suitable tool for this task is a mathematical equation representing the number of crashes as a function of the explanatory variables (potential risk factors). These equations are referred to as crash prediction models (or safety performance functions, SPFs). In case of roundabouts, SPFs may be of two kinds (*30*):

- *Intersection-level* SPFs relate the crash prediction to AADT and possibly other context variables, such as number of lanes or number of legs.
- *Approach-level* SPFs relate common types of crashes (e.g., approaching, entering-circulating, or exiting-circulating crashes) to specific AADTs and key geometric parameters (risk factors).

Analysis 1 – Safety performance functions

Review

Developing SPFs, as a tool of quantitative road safety management, is not a new activity. However, SPFs are usually defined for typical network elements (road segments and intersections). Many countries do not use any specific roundabout SPFs. For example in the US, although a number of roundabout SPFs were developed under NCHRP Project 3-65 (*30*). none of them was introduced in the current edition of *Highway Safety Manual* (HSM; *31*). The on-going NCHRP Project 17-70 aims to develop roundabout SPFs to be used in the second edition of HSM (*32*).

On the contrary, in New Zealand, with long tradition both in roundabout constructions and using SPFs, approach-level SPFs are firmly established and implemented in national evaluation guidelines (*33*). Also Nordic countries (Denmark, Sweden, Finland) are all using specific roundabout SPFs (*34 – 36*); however only on the intersection level. In the Czech Republic, roundabout SPFs were developed as well (*37 – 39*); however no Czech approach-level SPF exists.

Data

Given availability of traffic census (AADT) data on all legs, sample of 200 typical (unsignalized) roundabouts was selected for analysis. In order to study individual entries, each roundabout was split into individual leg segments.

Crash data were retrieved from 8 years (2009 – 2016), in a distance of 100m from the roundabout center (approx. 300 ft, based on *40*). In the Czech Republic, crash reporting is not routinely linked to specific types, such as entering-circulating crashes; therefore all crash types were used. Regarding their severity, approx. 77% were property-damage-only (PDO) crashes. Distinguishing individual severity levels would thus result in small samples. Therefore, alternative approach was tested: using national values of crash costs for severity levels (*41*), equivalent of PDO crashes (EPDO) was calculated (value 1 represents one PDO crash, and values 3.68, 32.70, 97.38 represent one slight, severe and fatal injury, respectively). In the analysis, both crash frequency and EPDO were used as a response variable.

As mentioned, AADT from national traffic census was used as a source of traffic volume data. This data however do not provide disaggregation into specific movements, such as entering, circulating, or exiting AADT.

Road and geometric characteristics were collected from online maps. During collection, it was found that conditions were changing during the 8-year period: there were cases, when for example, a bypass, pedestrian crossing, or even another roundabout leg was added. Therefore, each year was considered individually. AADT values were interpolated between years, according to national traffic forecasting guidelines (*42*); also EPDO was calculated separately for each year.

In a sum, the sample of 200 roundabouts comprised 781 approaches, separated into 8 annual records. After some data reduction, these resulted in a total of 5,193 data records. Based on literature review, following road and geometric variables were assigned to all the records:

- Intersection-level characteristics
  - Location (rural or urban)
  - Roundabout type (single-lane, double-lane, mini, turbo, grade separated)
  - Circular shape (no/yes)

  - Number of legs (3, 4, 5 or 6 legs)
  - Inscribed circle and central island diameter
  - Standard deviation of angles between legs (in case of perpendicular legs, standard deviation is zero; the variable shows the difference from the ideal configuration)
  - Number of circulatory lanes (1 or 2)
  - Circulatory lane width
  - Truck apron width
- Approach-level characteristics
  - Entry angle, Deviation angle, Exit angle (as previously defined)
  - Entry width, Exit width, Bypass width
  - Close proximity features (binary variables showing presence of public transport stop, parking, accesses or intersections, within 100m from roundabout)
  - Number of entry lanes and Number of exit lanes
  - Pedestrian crossing (no/yes)
  - Driving directions (entry, exit or both)
  - Alignment offset (offset of leg alignment from the radial direction)
  - Collision distance (distance between entry and following exit)

Exploratory analysis

The next step was exploratory analysis. During trials, it was found that categorization of some continuous variables improved their relationship to crash frequency. Therefore, selected variables were transformed as follows:

- Entry angle was categorized into 5 intervals: < 20°, (20°; 40°⟩, (40°; 60°⟩, (60°; 80°⟩, and > 80°.
- Bypass width, Truck apron width, and Alignment offset were transformed into binary absence/presence (no/yes).
- Instead of entry width, variable Entry type was created, using number of entry lanes and number of circulatory lanes:
  - E1 … 1 entry lane and 1 circulatory lane
  - E2 … 1 entry lane and 2 circulatory lanes
  - E3 … 2 entry lanes and 2 circulatory lanes

Next, correlations between all pairs of variables were checked. In case, when correlation coefficient exceeded 0.5 threshold, one of variables was removed. After these initial steps, 19 remaining variables were prepared for modeling. Table 1 summarizes this selection process.

TABLE 1 List of Variables, Transformations and Selection for Modeling

		Variable	Transformation	Inter-colleration	Modeling input
Intersection-level characteristics		Location			**Location**
		Roundabout type			**Roundabout type**
		Circular shape			**Circular shape**
		# legs			
		Inscribed circle diameter			**Inscribed circle diameter**
		Central island diameter			
		Std. dev. of angles between legs			**Std. dev. of angles between legs**
		# circulatory lanes			**# circulatory lanes**
		Circulatory lane width	Entry type categories		
		Truck apron width	Apron presence		**Apron presence**
Approach-level characteristics	Angles	Entry angle	Entry angle intervals		**Entry angle intervals**
		Deviation angle			
		Exit angle			
	Widths	Entry width	Entry type categories		
		Exit width	Entry type categories		
		Bypass width	Bypass presence		**Bypass presence**
	Close proximity features	Public transport stop			**Public transport stop**
		Parking			**Parking**
		Access			**Access**
		Different location			**Different location**
		Close intersection type			**Close intersection type**
	Other	Number of entry lanes			**Number of entry lanes**
		Number of exit lanes			**Number of exit lanes**
		Pedestrian crossing			**Pedestrian crossing**
		Driving directions			
		Alignment offset	Offset presence		
		Collision distance			**Collision distance**

Table 2 summarizes descriptive characteristics of this data.

TABLE 2 Descriptive Characteristics of Continuous and Categorical Variables

Continuous variables		**Min.**	**Max.**	**Mean**	**Std. Dev.**
Crash frequency		0	16	0.47	1.14
Crash severity (EPDO)		0	113.42	0.83	3.60
AADT [veh/day]		5	24520	4541.04	2813.22
Collision distance [m]		0	106	16.90	10.87
Inscribed circle diameter [m]		19	139	42.20	21.44
Std. dev. of angles between legs [°]		0	61	15.48	11.60
Categorical variables					
Access				*no* 42.1%	*yes* 57.9%
Apron presence				*no* 21.3%	*yes* 78.7%
Bypass presence				*no* 93.0%	*yes* 7.0%
Circular shape				*no* 4.7%	*yes* 95.3%
Close intersection type		*X* 18.2%	*T* 60.5%	*Y* 3.2%	*staggered* 1.8%
		star 0.5%	*roundabout* 8.9%	*grade-separated* 4.4%	*none* 2.4%
Different location				*rural* 21.1%	*urban* 78.9%
Entry angle	*⟨0°; 20°⟩* 14.4%	*(20°; 40°⟩* 47.2%	*(40°; 60°⟩* 33.6%	*(60°; 80°⟩* 3.5%	*none (exit only)* 1.3%
Entry type		*none (exit only)* 1.2%	*E1* 88.1%	*E2* 5.5%	*E3* 5.2%
Location				*rural* 20.7%	*urban* 79.3%
Number of circulatory lanes				*1* 90.5%	*2* 9.5%
Number of entry lanes			*0 (exit only)* 1.3%	*1* 94.4%	*2* 4.3%
Number of exit lanes			*0 (entry only)* 1.0%	*1* 95.4%	*2* 3.6%
Parking				*no* 84.2%	*yes* 15.8%
Pedestrian crossing				*no* 39.1%	*yes* 60.9%
Public transport stop				*no* 85.1%	*yes* 14.9%
Roundabout type	*single-lane* 88.5%	*double-lane* 8.4%	*mini* 2.0%	*turbo* 0.7%	*grade-separated* 0.4%

Modeling

Reported data was used to develop SPFs. Consistently with literature (e.g., *19*), the basic form comprised only exposure ($AADT$), with further explanatory variables (x_i) being added stepwise, keeping only the ones with achieved statistical significance below 5 %:

$$\hat{N} = \exp(\beta_0) \cdot (AADT)^{\beta_1} \cdot \exp\left(\sum_{i=2}^{n} (\beta_i \cdot x_i)\right) \quad (1)$$

where:
$\widehat{N}$ … expected annual crash frequency or crash severity (EPDO)
$AADT$ … exposure variable (daily traffic volume)
x_i … other explanatory variables (risk factors)
β_i … regression coefficients, to be estimated in modeling

Generalized linear modeling procedure in IBM SPSS was applied, using a negative binomial error structure with a logarithmic link function; AADT thus took form of natural logarithm $\ln(AADT)$. The linearized model form is shown in Eq. 2:

$$\ln(\widehat{N}) = \beta_0 + \beta_1 \cdot \ln(AADT) + \sum_{i=2}^{n}(\beta_i \cdot x_i) \qquad (2)$$

Results
During modeling, several insignificant variables were discarded. Table 3 reports parameters of final SPFs (crash frequency SPF and crash severity SPF): regression coefficients β_i and achieved levels of statistical significance (*Sig.*). Statistical significance was below 5% in most cases, with 2 exceptions (in bold), which had levels between 5% and 10%.

TABLE 3 Parameter of Crash Frequency SPF and Crash Severity (EPDO) SPF

		Crash frequency SPF		**Crash severity (EPDO) SPF**	
Variable	Category	β_i	*Sig.*	β_i	*Sig.*
(Intercept β_0)		–2.800	*0.000*	–2.940	*0.000*
ln (AADT)		0.583	*0.000*	0.583	*0.000*
Collision distance		–0.005	*0.012*	–0.009	*0.014*
Std. dev. of angles between legs		0.005	*0.024*	0.006	*0.028*
Entry angle	< 20°	–0.952	*0.002*	–0.946	***0.097***
	(20°; 40°⟩	–1.183	*0.000*	–1.239	*0.028*
	(40°; 60°⟩	–1.169	*0.000*	–1.212	*0.031*
	(60°; 80°⟩	–1.122	*0.000*	–1.178	*0.041*
	> 80°	0		0	
Apron	no	0.560	*0.000*	0.703	*0.000*
	yes	0		0	
Bypass	no	–0.498	*0.000*	–0.521	*0.000*
	yes	0		0	
Entry type	E1	–1.813	*0.000*	–1.996	*0.000*
	E2	–1.123	*0.000*	–1.277	*0.000*
	E3	0		0	
Location	rural			0.188	*0.017*
	urban			0	
Pedestrian crossing	no			–0.133	***0.068***
	yes			0	

Interpretation

Regression coefficients in Table 3 are consistent between Crash frequency SPF and Crash severity (EPDO) SPF. Using the latter enabled identifying also the influence of Location and Pedestrian crossing, which were not statistically significant in the former SPF.

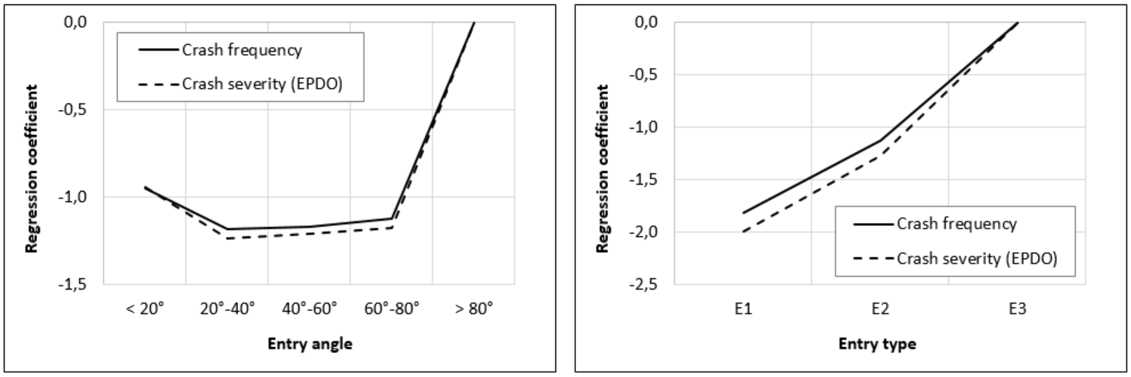
Signs of regression coefficients β_i enable interpreting directions of influence of individual variables on response variable:

- Positive relationship means that change of a variable is associated with change of response variable in the same direction. Therefore, increasing variable increases crash frequency/severity, and decrease of variable decreases crash frequency/severity.
- Negative relationship that change of a variable is associated with change of response variable in the opposite direction. Therefore, increasing variable decreases crash frequency/severity, and decrease of variable increases crash frequency/severity.

Effects of categorical variables are to be interpreted in comparison to the reference category (i.e., the one with zero regression coefficient). For example, missing pedestrian crossing ("no") has a negative coefficient, thus it is associated with lower crash frequency, compared to the reference category with pedestrian crossing ("yes").

According to Table 3, the variables had following directions of influence:

- AADT has a positive influence as expected. In addition, coefficient 0.583 is close to values 0.576 from previous Czech SPF (*39*) or 0.58 from New Zealand SPF (*33*, Table 15).
- Collision distance has a negative association: the longer distance, the more space for potential evasive manoeuvers and lower crash frequency/severity. This was confirmed also by Maycock & Hall (*19*) or Arndt (*23*).
- Standard deviation of angles between legs has a positive relationship (the more dispersion, the more complex environment and higher crash frequency/severity), consistently with Czech design standards. Also Jensen (*43*) noted that "as the difference between the smallest and largest angle between arms in a roundabout becomes smaller, the level of safety becomes better."
- Regression coefficients for entry angle are displayed in Fig. 1a. The curve has minimum values between 20° and 80°. This is relatively consistent Spanish and British standards, which recommend interval of entry angles 20° – 60° (*25*, *26*).
- Fig. 1b provides analogical graph for entry types. The trend is rising from E1 (single entry and circulatory lane) to E3 (two entry and circulatory lanes). Positive association between entry width (number of lanes) and crash frequency was identified in several studies (*19, 9, 44, 37, 45*).
- Truck apron has a protective influence: its presence is associated with lower crash frequency/severity. This was also confirmed by Šenk & Ambros (*37*).
- On the contrary, bypass presence is associated with higher crash frequency/severity. This is probably due to adding another conflict point, which increases crash risk and severity, as noted by Robinson et al. (*9*) or Daniels et al. (*46*).
- Location in rural areas seems to increase crash severity, compared to urban roundabouts; the same holds for presence of pedestrian crossing. Both variables are likely to be associated with speed and vulnerability, as also reported by Turner et al. (*44*) or Šenk & Ambros (*37*).



(a) (b)

FIGURE 1 Regression coefficients for categories of (a) entry angle and (b) entry type.

“Location” variable is likely to be a proxy for speed, which was not considered in SPF. In this regards, it would be interesting to measure speed and use it in modeling. Therefore, alternative approach was used for the second analysis step: speeds were measured on a sub-sample of roundabouts and used to explore its relationship to roundabout geometry.

Analysis 2 – Speed

Review

Traditionally, speed measurement has been performed using stationary devices. For example, Rodegerdts et al. (*30*) used speed gun to measure free-flow speeds in specific points of through-pass trajectory; similar approach was used also by Spacek (*8*), Turner et al. (*44*) or Kim & Choi (*47*). In addition to speed guns, some (*48*, *49*) measured speeds of isolated vehicles also by video camera. However, with these methods speeds are collected only in limited spots. Therefore, alternative methods used video detection or image processing to obtain complete speed profiles (*50 – 52*). Other studies used speed data collected by car-following (“car-chase method”, mentioned in *21*, or “floating vehicle”, *53*) or by instrumented vehicles (e.g., *54*).

Data

In this study, instrumented vehicle of CDV – Transport Research Centre was used. It is a common van, equipped by data collection sensors (GPS, accelerometers, gyroscopes, video camera). GPS location was operating at 10 Hz frequency (10 records per second), with horizontal precision of 1 meter. It was used to obtain data points, representing vehicle path and continuous speed. Data were collected on a sub-sample of 11 roundabouts, where two drivers passed several times through each leg, totaling 92 through-drives from one leg to the opposite one. Driving was conducted in free-flow conditions (morning and evening off-peak periods).

Collected data were processed to obtain relevant radii and angles, distinguish tangent and curve segments and estimate respective speeds. The obtained parameters were:

- Radii on entry, center and exit
- Entry angle, deviation angle, exit angle
- Speeds in seven profiles (A to G):
    - A … on approach leg (50m upstream of entry)
    - 5 profiles at a roundabout (B, C, D, E, F)
    - G … on exit leg (50m downstream of exit)

The parameters, together with an example of speed profiles, are displayed in Fig. 2.

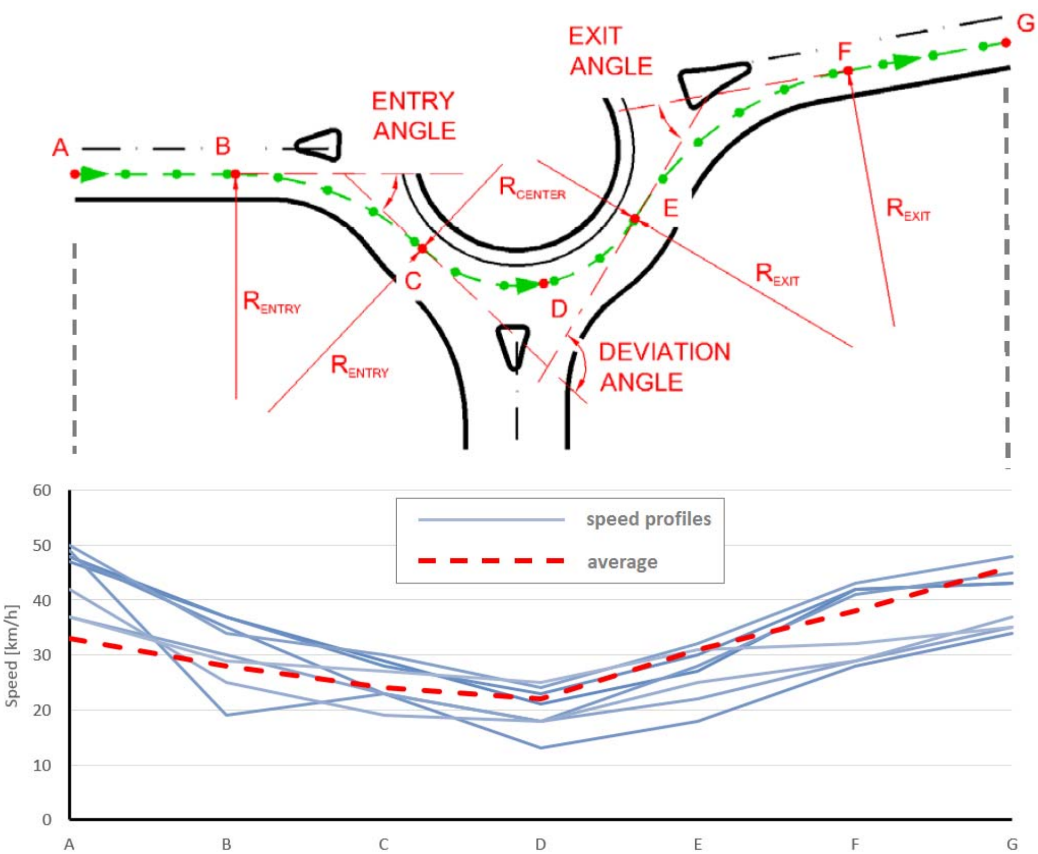


FIGURE 2 Through-pass trajectory parameters and example of speed profiles.

Results

To assess the influence of radii and angles on speed, Spearman correlation coefficients were calculated. Unfortunately, only some exceeded 0.5 threshold, which is perceived as a threshold of moderate correlation (*55*). These were correlations between:

- speed 50m upstream of entry and entry angle
- speed 50m upstream of entry and entry radius
- speed in center and central radius

The first two associations relate to roundabout entries, which indicates their relationship to safety. In the first analysis, link between geometry and safety was established through crash frequency/severity SPFs; the second analysis showed the link between geometry and speed. One may thus anticipate a causal chain: geometry – speed – safety. In order to confirm existence of this chain, the third analysis attempted to develop SPF, which contain both geometry and speed variables.

Analysis 3 – Safety performance functions with speed

Review

Several international studies employed speed variables in their SPFs (e.g., *56, 23, 44, 57*). On the other hand, some of them did not succeed, for example NCHRP Project 3-65 (*30*), where estimated model was deemed inadequate on the basis of weak effects of speed variables. One of problems may be the use of different speed definitions, such as speed limits, measured speeds, predicted/simulated speeds, etc. Other authors attempted estimating speed from geometric parameters, and then using it to model crash frequencies (*58, 49, 59*). These studies differed in using measured or predicted speeds, and in function form of speed (either power or exponential form). It is thus evident that although developing speed-based SPFs is not a new task, it is still not a formalized approach.

Data

This analysis was based on previously described data collected at 11 roundabouts. Following variables were used:

- crash frequency or crash severity as a response variable, collected for each through-pass
- angles and radii as explanatory variables
- speeds in profiles A to G as additional explanatory variables

Instead of AADT, hourly traffic flow in respective trajectories, was counted on the site. Descriptive characteristics of data are reported in Table 4.

TABLE 4 Descriptive Characteristics of Crash, Geometry and Speed Data

Variable	Unit	Min.	Max.	Mean	Std. Dev.
Crash frequency	[-]	1	25	9.26	6.60
EPDO	[-]	1	59.22	15.69	14.50
Hourly traffic flow	[veh/h]	64	1600	548.93	488.00
Entry angle	[°]	2	75	34.37	15.93
Deviation angle	[°]	40	191	79.56	32.04
Exit angle	[°]	8	52	31.48	11.73
Entry radius	[m]	18	113	36.59	18.39
Central radius	[m]	12	28	19.67	3.81
Exit radius	[m]	25	92	38.04	13.80
Speed A	[km/h]	31	54	42.33	6.34
Speed B	[km/h]	23	40	31.63	4.13
Speed C	[km/h]	21	35	26.93	3.35
Speed D	[km/h]	18	30	24.44	2.94
Speed E	[km/h]	23	40	31.04	3.54
Speed F	[km/h]	28	50	38.00	4.92
Speed G	[km/h]	30	64	44.41	8.71

Results

The model form described in Equation 1 was used (with hourly traffic flow instead of AADT). Apart from traffic flow, the SPF introduce entry angle, and speed 50m upstream of entry. Parameters of developed SPF (regression coefficients β_i and achieved levels of statistical significance, all below 5%) are reported in Table 5.

TABLE 5 SPF Parameters

Variable	β_i	*Sig.*
(Intercept β_0)	5.211	*0.022*
ln (hourly traffic flow)	–0.727	*0.007*
Entry angle	–0.052	*0.001*
Speed 50m upstream of entry	0.066	*0.031*

Typically, AADT has a positive relationship to crash frequency; on the contrary, negative coefficient of traffic flow was found in all three SPFs. Although not expected, several studies also had such finding:

- Satterthwaite (*60*) found that rear-end crash rates increased with traffic flow, while single-vehicle rates decreased.
- Hiselius (*61*) identified similar confusion, when mixing volumes of cars and trucks.
- Analysis by Christoforou et al. (*62*) concluded that low volume (free-flow) conditions may lead to higher speeds, which in turns cause unexpected direction of traffic flow influence on safety. The unexpected sign of regression coefficient may be thus due to using aggregated input data.

Signs of other regression coefficients are as expected from literature:

- Entry angle has a protective effect: the higher angle, the lower speed and risk.
- Speed on approach has a positive relationship to crashes: increasing speed is associated to increasing crash frequency.

DISCUSSION AND CONCLUSIONS

The study comprised three analyses: crash-based safety performance functions (SPFs), speed analysis, and finally SPFs which incorporated speed. The analyses were different in terms of their data needs: while crash-based SPFs required crashes, traffic volumes and geometry (i.e., data that are usually available network-wide), the second and third approach required speed data, that had to be especially collected. This is why samples were different (200 roundabouts in Analysis 1 vs. 11 roundabouts in Analyses 2 and 3). On the other hand, using speed in analyses adds an extra value, since it may be considered a proxy for driving behavior, which is likely to enhance the quality of developed models.

With the aim of investigating the influence of roundabout entry design parameters on safety, the analyses concluded as follows:

- Analysis 1 developed approach-level SPFs. Consistently with literature, a number of variables were significantly related to crashes, including entry angle and entry type. Using crash severity (EPDO) in addition to crash frequency also enabled revealing significant influence of location (rural/urban) and presence of pedestrian crossing on roundabout leg.
- In analysis 2, speeds were measured on a sub-sample of roundabouts and used to explore its relationship to roundabout geometry. Correlation was found between approach speeds (50m upstream of entry) and entry angle and entry radius.
- Analysis 3 successfully incorporated approach speed into SPF and confirmed that increasing speed is associated to increasing crash frequency; again it was demonstrated that entry angle has a protective effect.

Thus, it was proved that entry design parameters have a statistically significant influence on safety, in terms of crash frequency, severity and speeds. The SPF suggested suitable range of entry angle values, which should be considered in Czech roundabout design guidelines TP 135 (*63*). Currently they only recommend a deviation of entry trajectory from entry axis, which may not be sufficient to reach necessary speed reduction of vehicles entering circulatory lane. The analysis also identified the influence of entry radius; at the same, Czech guidelines mention verification of fastest path radii, but without mentioning any specific values of entry or radii.

At the same time, the authors are aware of several limitations:

- Input crash data is likely to be underreported. In addition, routine crash reporting does not allow distinguishing individual crash types.
- Routinely collected AADT data, which does not consider individual movements, are also not ideal.
- Through-pass trajectory identification was based on circular elements only, without consideration of transition curves.
- Speed data was collected only by one instrumented vehicle and two drivers, which may not provide representative speed behavior data. Sample of 11 roundabouts, where speeds were measured, was also small.

Further activities should aim to expand sample size and consider the mentioned limitations of crash, AADT and speed data. Nevertheless, the presented results indicate existence of a causal chain: geometry – speed – safety. The study found that:

1. Both crash frequency and severity is influenced by roundabout entry geometry.
2. At the same time, the geometry influences driving speeds.
3. Safety performance is thus dictated by both geometry and speeds.

In future, these points may be further elaborated to develop a "two-stage" tool for roundabout safety analysis (*49*). In its first stage, speed may be modeled based on geometry and used in the second stage as a surrogate safety measure (instead of crash-based measures) to assess safety, even during the planning phase.

ACKNOWLEDGMENTS

The authors appreciate the help of their colleagues Lucie Vyskočilová, Ondřej Gogolín and Martin Kovář with data collection and processing. The study also benefited from the work of Giuseppe Trovato during his research stay at CDV, organized by University of Catania and Brno University of Technology. The study was conducted with the financial support of Czech Ministry of Education, Youth and Sports under the National Sustainability Programme I project of Transport R&D Centre, using the research infrastructure from the Operation Programme Research and Development for Innovations.

REFERENCES

1. Ogden, K. W. *Safer Roads: A Guide to Road Safety Engineering*. Ashgate, Aldershot, 1997.
2. *Road Safety Manual: recommendations from the World Road Association (PIARC).* Route2market, Harrogate, 2003.
3. Elvik, R., A. Høye, T. Vaa, and M. Sørensen. *The Handbook of Road Safety Measures, Second Edition*. Emerald, Bingley, 2009.
4. Tiwari, G., and D. Mohan (Eds.). *Transport Planning & Traffic Safety: Making Cities, Roads, & Vehicles Safer*. CRC Press, Boca Raton, 2016.

5. FHWA. *Intersection Safety*. https://www.fhwa.dot.gov/research/topics/safety/intersections/. Accessed July 26, 2017.
6. European Commission. *Basic Traffic Safety Facts 2015*. https://ec.europa.eu/transport/road_safety/specialist/statistics_en. Accessed July 26, 2017.
7. Rodegerdts, L., J. Bansen, C. Tiesler, J. Knudsen, E. Myers, M. Johnson et al. *NCHRP Report 672: Roundabouts: An Informational Guide, Second Edition*. Transportation Research Board, Washington, D.C., 2010.
8. Spacek, P. Basis of the Swiss Design Standard for Roundabouts. *Transportation Research Record: Journal of the Transportation Research Board*, No.1881, 2004, pp. 27–35. http://dx.doi.org/10.3141/1881-04
9. Robinson, B. W. (Ed.). *Roundabouts: An Informational Guide*. Report FHWA-RD-00-067. FHWA, U.S. Department of Transportation, 2000.
10. Isebrands, H. N. (Ed.). Enhancing Intersection Safety Through Roundabouts: An ITE Informational Report. ITE, Washington, D.C., 2008.
11. Montella, A. Roundabout In-Service Safety Reviews: Safety Assessment Procedure. *Transportation Research Record: Journal of the Transportation Research Board*, No. 2019, 2007, pp. 40–50. http://dx.doi.org/10.3141/2019-06
12. Ambros, J., R. Turek, and Z. Janoška. Safety evaluation of Czech roundabouts. *Advances in Transportation Studies*, Vol. 40, 2016, pp. 111–122. http://dx.doi.org/10.4399/97888548970079
13. Slabý, P., J. Kocourek, and D. Kočárková. Analýza vlivu vybraných stavebních opatření. Part IV of BESIDIDO project final report. Czech Technical University in Prague, Prague, 2005.
14. Montella, A. Identifying crash contributory factors at urban roundabouts and using association rules to explore their relationships to different crash types. *Accident Analysis & Prevention*, Vol. 43, 2011, pp.1451–1463. http://dx.doi.org/10.1016/j.aap.2011.02.023
15. Persaud, B. N., R. A. Retting, P. E. Garder, and D. Lord. Safety effect of roundabout conversions in the United States: empirical Bayes observational before-after study. *Transportation Research Record: Journal of the Transportation Research Board*, No. 1751, 2001, pp. 1–8. http://dx.doi.org/10.3141/1751-01
16. Elvik, R. Effects on road safety of converting intersections to roundabouts: review of evidence from non-US studies. *Transportation Research Record: Journal of the Transportation Research Board*, No. 1847, 2003, pp. 1–10. http://dx.doi.org/10.3141/1847-01
17. Elvik, R. Road safety effects of roundabouts: A meta-analysis. *Accident Analysis & Prevention*, Vol. 99, 2017, pp. 364–371. http://dx.doi.org/10.1016/j.aap.2016.12.018
18. Mandavilli, S., A. McCartt, and R. Retting. Crash patterns and potential engineering countermeasures at Maryland roundabouts. *Traffic Injury Prevention*, Vol. 10, 2009, pp. 44-50. http://dx.doi.org/10.1080/15389580802485938
19. Maycock, G., and R. D. Hall. *Accidents at 4-arm roundabouts*. Laboratory Report 1120. Transport and Road Research Laboratory, Crowthorne, 1984.
20. Brilon, W., and M. Vandehey. Roundabouts – The State of the Art in Germany. ITE Journal, November 1998, pp. 48–54.
21. Hydén, C., and A. Várhelyi. The effects on safety, time consumption and environment of large scale use of roundabouts in an urban area: a case study. *Accident Analysis & Prevention*, Vol. 32, 2000, pp. 11–23. http://dx.doi.org/10.1016/S0001-4575(99)00044-5
22. Overkamp, D. P., and W. van der Wijk. *Roundabouts – Application and design: A practical manual*. Ministry of Transport, Public Works and Water Management, The Hague, 2009.

23. Arndt, O. K. *Relationship Between Unsignalised Intersection Geometry and Accident Rates*. PhD thesis. Queensland University of Technology, Brisbane, 2004.
24. Kennedy, J. *International comparison of roundabout design guidelines*. Published project report PPR206. Transport Research Laboratory, Crowthorne, 2007.
25. *Recomendaciones sobre glorietas*. Dirección General de Carreteras, Madrid, 1999.
26. *Design Manual for Roads and Bridges, TD 16/07.* http://www.standardsforhighways.co.uk/ha/standards/dmrb/vol6/section2/td1607.pdf. Accessed July 26, 2017.
27. *Knoten mit Kreisverkehr / Carrefours giratoires*. Swiss Standard SN 640 263. Association of Swiss Road and Traffic Engineers, Zurich, 1999.
28. Montella, A., S. Turner, S. Chiaradonna, and D. Aldridge. International overview of roundabout design practices and insights for improvement of the Italian standard. *Canadian Journal of Civil Engineering*, Vol.40, 2013, pp. 1215–1226. http://dx.doi.org/10.1139/cjce-2013-0123
29. Arndt, O., and R. Troutbeck. Techniques for analysing the effect of road geometry on accident rates using multifactor studies. Presented at 22nd ARRB Conference, Canberra, 2006.
30. Rodegerdts, L., M. Blogg, E. Wemple, E. Myers, M. Kyte, M. Dixon et al. *NCHRP Report 572: Roundabouts in the United States*. Transportation Research Board, Washington, D.C., 2007.
31. *Highway Safety Manual, First Edition*. AASHTO, Washington, D.C., 2010.
32. Foster, N. NCHRP Project 17-70 Development of Roundabout Crash Prediction Models and Method. Presented at 5th International Conference on Roundabouts, Green Bay, 2017.
33. *Crash Estimation Compendium (New Zealand Crash Risk Factors Guideline).* NZ Transport Agency, Wellington, 2016.
34. Jensen, S. U. Uheldsmodeller for rundkørsler. *Trafik & Veje*, June/July 2013, pp. 54–55.
35. *Bygg om eller bygg nytt, Kapitel 6 Trafiksäkerhet*. Trafikverket, Borlänge, 2016.
36. Peltola, H., R. Rajamäki, and J. Luoma. A tool for safety evaluations of road improvements. *Accident Accident Analysis & Prevention*, Vol. 60, 2013, pp. 277–288. http://dx.doi.org/10.1016/j.aap.2013.04.008
37. Šenk, P., and J. Ambros. Estimation of Accident Frequency at Newly-built Roundabouts in the Czech Republic. *Transactions on Transport Sciences*, Vol. 4, 2011, pp. 199–206. http://dx.doi.org/10.2478/v10158-011-0018-4
38. Novák, J., and J.Ambros. Rozšíření predikčního modelu nehodovosti na okružních křižovatkách. Presented at 20. Silniční konference, Plzeň, 2012.
39. Ambros, J., and P. Slabý. Comparison of Roundabout Accident Prediction Models: Challenges of Data Collection, Analysis and Interpretation. Presented at 20th Anniversary of the Faculty of Transportation Sciences, Prague, 2013.
40. Avelar, R. E., K. K. Dixon, and P. Escobar. Evaluation of Signalized-Intersection Crash Screening Methods Based on Distance from Intersection. *Transportation Research Record: Journal of the Transportation Research Board*, No. 2514, 2015, pp. 177–186. http://dx.doi.org/10.3141/2514-19
41. Vyskočilová, A., O. Gogolín, and O.Valach. New Approach to Evaluation of Socio-economic Losses Caused by Traffic Accidents. Presented at 93rd TRB Annual Meeting, Washington, D.C., 2014
42. Bartoš, L., A. Richtr, J. Martolos, and M. Hála. *Prognóza intenzit automobilové dopravy, II. vydání*. Technical guidelines 225. EDIP s.r.o., Plzeň, 2012.
43. Jensen, S. U. Safety Effects of Height of Central Islands, Sight Distances, Markings and Signage at Single-lane Roundabouts. Presented at 5th International Symposium on Highway Geometric Design, Vancouver, 2015.

44. Turner, S. A., A. P. Roozenburg, and A. W. Smith. *Roundabout crash prediction models*. Research Report 386. NZ Transport Agency, Wellington, 2009.
45. Ambros, J., J. Novák, A. Borsos, E. Hóz, M. Kieć, Š. Machciník, and R. Ondrejka. Central European Comparative Study of Traffic Safety on Roundabouts. *Transportation Research Procedia*, Vol. 14, 2016, pp. 4200–4208. http://dx.doi.org/10.1016/j.trpro.2016.05.391
46. Daniels, S., T. Brijs, E. Nuyts, and G. Wets. Extended prediction models for crashes at roundabouts. *Safety Science*, Vol. 49, 2011, pp. 198–207. http://dx.doi.org/10.1016/j.ssci.2010.07.016
47. Kim, S., and J. Choi. Safety Analysis of Roundabout Designs based on Geometric and Speed Characteristics. *KSCE Journal of Civil Engineering*, Vol.17, 2013, pp. 1446–1454. http://dx.doi.org/10.1007/s12205-013-0177-4
48. Bassani, M., and E. Sacchi. Experimental Investigation into Speed Performance and Consistency of Urban Roundabouts: An Italian Case Study. Presented at 3rd International Conference on Roundabouts, Carmel, 2011.
49. Chen, Y., B. Persaud, E. Sacchi, and M. Bassani. Investigation of models for relating roundabout safety to predicted speed. *Accident Analysis & Prevention*, Vol. 50, 2013, pp. 196–203. http://dx.doi.org/10.1016/j.aap.2012.04.011
50. Guido, G., F. Saccomanno, A. Vitale, V. Astarita, and D. Festa. Comparing Safety Performance Measures Obtained from Video Capture Data. *Journal of Transportation Engineering*, Vol. 137, 2011, pp. 481–491. http://dx.doi.org/10.1061/(ASCE)TE.1943-5436.0000230
51. Mussone, L., M. Matteucci, M. Bassani, and D. Rizzi. An innovative method for the analysis of vehicle movements in roundabouts based on image processing. *Journal of Advanced Transportation*, Vol. 47, 2013, pp. 581–594. http://dx.doi.org/10.1002/atr.184
52. Sadeq, H., and T. Sayed. Automated Roundabout Safety Analysis: Diagnosis and Remedy of Safety Problems. *Journal of Transportation Engineering*, Vol. 142, 2016, 04016062. http://dx.doi.org/10.1061/(ASCE)TE.1943-5436.0000887
53. Gaca S., and M. Kieć. Speed Management for Local and Regional Rural Roads. *Transportation Research Procedia*, Vol. 14, 2016, pp. 4170–4179. http://dx.doi.org/10.1016/j.trpro.2016.05.388
54. Bastos Silva, A., S. Santos, L. Vasconcelos, Á. Seco, and J. P. Silva. Driver behavior characterization in roundabout crossings. *Transportation Research Procedia*, Vol. 3, 2014, pp. 80–89. http://dx.doi.org/10.1016/j.trpro.2014.10.093
55. Hinkle, D. E., W. Wiersma, and S. G. Jurs. *Applied Statistics for the Behavioral Sciences, 5th Edition*. Cengage Learning, Boston, 2003.
56. Brüde, U., and J. Larsson. What roundabout design provides the highest possible safety? *Nordic Road & Transport Research*, No. 2, 2000, pp.17–21.
57. Farag, S. G., and I. H. Hashim. Safety performance appraisal at roundabouts: Case study of Salalah City in Oman. *Journal of Transportation Safety & Security*, Vol. 9, 2017, pp. 67–82. http://dx.doi.org/10.1080/19439962.2016.1199623
58. Chen, Y., B. Persaud, and C. Lyon. Effect of speed on roundabout safety performance – Implications for use of speed as a surrogate measure. Presented at 90th TRB Annual Meeting, Washington, D.C., 2011.
59. Lyon, C., S. Chan, and B. Persaud. A Model for Average Speed Estimation and Crash Prediction Using Vehicle Path Data. Presented at 4th International Conference on Roundabouts, Seattle, 2014.
60. Satterthwaite, S. P. *A survey of research into relationships between traffic accidents and traffic volumes.* Supplementary Report 692. Transport and Road Research Laboratory, Crowthorne, 1981.

61. Hiselius, L. W. Estimating the relationship between accident frequency and homogeneous and inhomogeneous traffic flows. *Accident Analysis & Prevention*, Vol. 36, 2004, pp. 985–992. http://dx.doi.org/10.1016/j.aap.2003.11.002
62. Christoforou, Z., S. Cohen, and M. G. Karlaftis. Integrating Real-Time Traffic Data in Road Safety Analysis. *Procedia – Social and Behavioral Sciences*, Vol. 48, 2012, pp. 2454–2463. http://dx.doi.org/10.1016/j.sbspro.2012.06.1216
63. Smělý, M., M. Radimský, and M. Patočka. *Projektování okružních křižovatek na silnicích a místních komunikacích, 3. vydání.* Technical guidelines 135. Brno University of Technology, Brno, 2017.