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How Roundabout Entry Design Parameters Influence Safety

Jan Novák[1], Jiří Ambros[1], and Jindřich Frič[1]

Abstract

Roundabouts are considered the safest intersection design; however, the 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 investigate how 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.

Intersections, where road users may change their directions 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 several 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, roundabouts are considered the safest intersection design, as they introduce few conflict points and low speeds, which are associated with reduction in the 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 include, 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 the early 2000s, may be one such example. In fact, Czech roundabout safety performance was found inferior, compared with other European countries (*12*), which may be due to insufficient roundabout experience, both in terms of design practice and driving performance. Similar 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 investigate how entry design parameters influence safety on Czech roundabouts. Driving behavior on roundabout entries is likely to be influenced by driving path geometry, sight conditions, and so forth. However, the impact of these influences 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 United States (*15*) found 40% reduction of all crashes, 80% of injury crashes, and 90% of fatal crashes. Meta-analysis of 28 non-U.S. studies (*16*) showed 30% to 50% injury crash reduction; fatal crashes were reduced by

[1]CDV – Transport Research Centre, Brno, Czech Republic

Corresponding Author:
Address correspondence to Jan Novák: jan.novak@cdv.cz

50% to 70%. A Czech before–after study (*12*) identified approximately 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 for example by 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 U.S. study, entering–circulating crashes were found to represent about three quarters of all collisions (*18*); above-average numbers of up to 71% were also identified in samples from the United Kingdom (*19*) and 57% in Switzerland (*8*).

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, almost 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 the central island). 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 (*7*). 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*). To take account of 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*). A 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 the case of roundabouts, SPFs may be of two kinds (*30*):

- Intersection-level SPFs relate the crash prediction to annual average daily traffic (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 United States, although several 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 a 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 the availability of AADT data on all legs, a sample of 200 typical (unsignalized) roundabouts was selected for analysis. To study individual entries, each roundabout was split into individual leg segments.

Crash data were retrieved from 8 years (2009–2016), for a distance of 100 m (approx 300 ft) from the roundabout center, based on Avelar et al. (*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, approximately 77% were property-damage-only (PDO) crashes. Distinguishing individual severity levels would thus result in small samples. Therefore, an 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 in which, 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 summary, 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, the 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 or yes);
  - Number of legs (3, 4, 5, or 6 legs);
  - Inscribed circle and central island diameter;
  - Standard deviation (SD) of angles between legs (SD is zero for perpendicular legs; the variable shows the difference from the ideal configuration);
  - Number of circulatory lanes (1 or 2);
  - Circulatory lane width; and
  - 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 100 m from roundabout);
  - Number of entry lanes and Number of exit lanes;
  - Pedestrian crossing (no or yes);
  - Driving directions (entry, exit, or both);
  - Alignment offset (offset of leg alignment from the radial direction); and
  - 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 or presence (no or yes).
- Instead of entry width, variable Entry type was created, using number of entry lanes and number of circulatory lanes:
  - E1 is 1 entry lane and 1 circulatory lane;
  - E2 is 1 entry lane and 2 circulatory lanes; and
  - E3 is 2 entry lanes and 2 circulatory lanes.

Table 1. List of Variables, Transformations and Selection for Modeling

Variable	Transformation	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		
SD of angles between legs		SD 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

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

Table 2 summarizes descriptive characteristics of the data.

Modeling. Reported data was used to develop SPFs. Consistent with the literature (*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 %

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

where

$\hat{N}$ = expected annual crash frequency or crash severity (EPDO),

AADT = exposure variable (daily traffic volume),

x_i = other explanatory variables (risk factors), and

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 the form of natural logarithm ln(AADT). The linearized model form is

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

Results. During modeling, several insignificant variables were discarded. Table 3 reports parameters of the 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 two exceptions (in bold), which had levels between 5% and 10%.

Table 2. Descriptive Characteristics of Continuous and Categorical Variables

		Min.	Max.	Mean	SD
Continuous variables					
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	yes
				42.1%	57.9%
Apron presence				no	yes
				21.3%	78.7%
Bypass presence				no	yes
				93.0%	7.0%
Circular shape				no	yes
				4.7%	95.3%
Close intersection type		X	T	Y	staggered
		18.2%	60.5%	3.2%	1.8%
		star	roundabout	grade-separated	none
		0.5%	8.9%	4.4%	2.4%
Different location				rural	urban
				21.1%	78.9%
Entry angle	0°;20°>	(20°;40°	(40°;60°>	(60°;80°>	none (exit only)
	14.4%	47.2%	33.6%	3.5%	1.3%
Entry type		none (exit only)	E1	E2	E3
		1.2%	88.1%	5.5%	5.2%
Location				rural	urban
				20.7%	79.3%
Number of circulatory lanes				1	2
				90.5%	9.5%
Number of entry lanes			0 (exit only)	1	2
			1.3%	94.4%	4.3%
Number of exit lanes			0 (entry only)	1	2
			1.0%	95.4%	3.6%
Parking				no	yes
				84.2%	15.8%
Pedestrian crossing				no	yes
				39.1%	60.9%
Public transport stop				no	yes
				85.1%	14.9%
Roundabout type	single-lane	double-lane	mini	turbo	grade-separated
	88.5%	8.4%	2.0%	0.7%	0.4%

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

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

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*
SD 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	

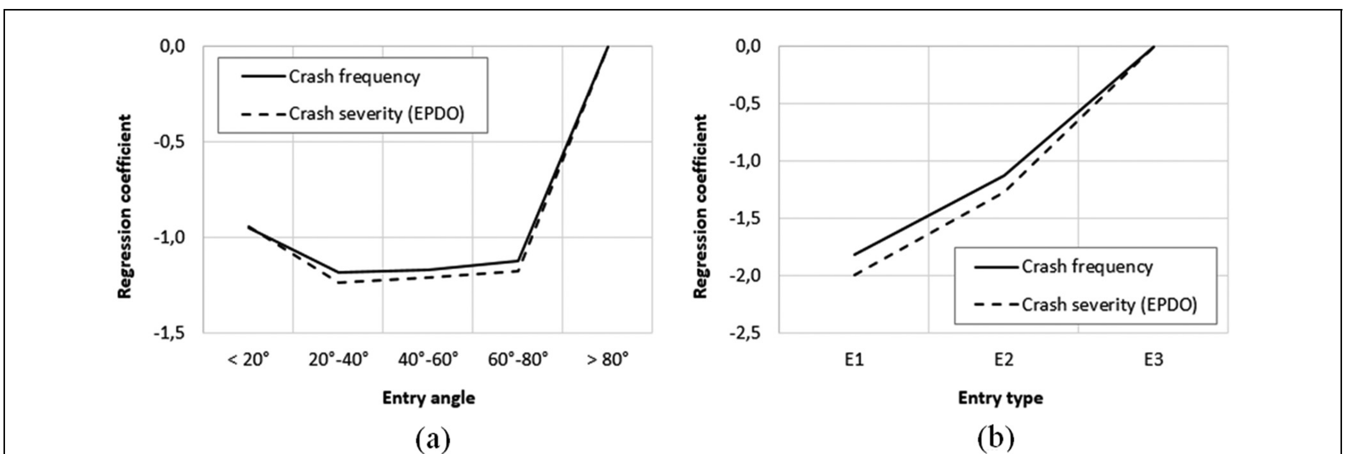

Figure 1. Regression coefficients for categories of (*a*) entry angle and (*b*) entry type.

associated with lower crash frequency, compared to the reference category with pedestrian crossing ("yes").

According to Table 3, the variables had the 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 the distance, the more space for potential evasive maneuvers and lower crash frequency or severity. This was confirmed also by Maycock & Hall (*19*) or Arndt (*23*).
- SD of angles between legs has a positive relationship (the more dispersion, the more complex the environment and the higher the crash frequency or severity), consistent 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 Figure 1*a*. The curve has minimum values between 20° and 80°. This is relatively consistent

with Spanish and British standards, which recommend interval of entry angles 20° to 60° (*25*, *26*).

- Figure 1*b* 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 (*9*, *19*, *37*, *44*, *45*).
- Truck apron has a protective influence: its presence is associated with lower crash frequency or severity. This was also confirmed by Šenk & Ambros (*37*).
- On the contrary, bypass presence is associated with higher crash frequency or 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*).

Location variable is likely to be a proxy for speed, which was not considered in the SPF. In this regard, it would be interesting to measure speed and use it in modeling. Therefore, an 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 a speed gun to measure free-flow speeds in specific points of through-pass trajectory. A similar approach was used also by Spacek (*8*), Turner et al. (*44*), and Kim & Choi (*47*). In addition to speed guns, some measured speeds of isolated vehicles also by video camera (*48*, *49*). 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 (*21*, *53*) or by instrumented vehicles (*54*).

Data. In this study, the CDV – Transport Research Centre instrumented vehicle 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 m. 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; and
- Speeds in seven profiles (A to G):
  - A, on approach leg (50 m upstream of entry);
  - 5 profiles at a roundabout (B, C, D, E, F); and
  - G, on exit leg (50 m downstream of exit).

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

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 50 m upstream of entry and entry angle;
- speed 50 m upstream of entry and entry radius; and
- 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 or severity SPFs; the second analysis showed the link between geometry and speed. One may thus anticipate a causal chain: geometry – speed – safety. 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., *23*, *44*, *56*, *57*). On the other hand, some of the studies did not succeed, for example NCHRP Project 3-65 (*30*), in which the estimated model was deemed inadequate on the basis of weak effects of speed variables. One of the problems may be the use of different speed definitions, such as speed limits, measured speeds, predicted or simulated speeds, and so forth. Other authors attempted estimating speed from geometric parameters, and then using it to model crash frequencies (*49*, *58*, *59*). These studies differed in using

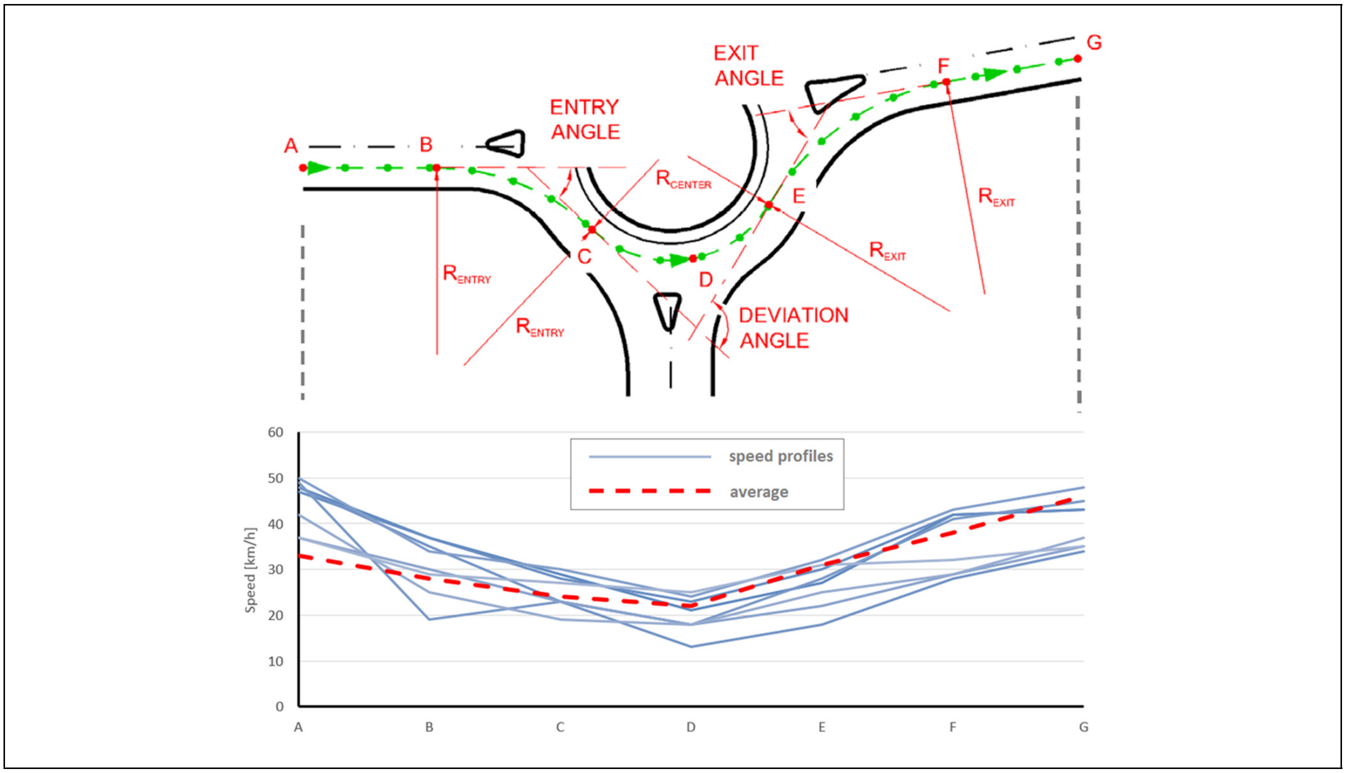

Figure 2. Through-pass trajectory parameters and example of speed profiles.

Table 4. Descriptive Characteristics of Crash, Geometry and Speed Data

Variable	Unit	Min.	Max.	Mean	SD
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

measured or predicted speeds, and in the 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. The following variables were used:

- Crash frequency or crash severity as a response variable, collected for each through-pass;
- Angles and radii as explanatory variables; and
- 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 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 50 m upstream of entry	0.066	*0.031*

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

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 turn 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 the angle, the lower the 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: whereas 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 the reason 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. Consistent with the literature, several variables were significantly related to crashes, including entry angle and entry type. Using crash severity (EPDO) in addition to crash frequency also revealed significant influence of location (rural or urban) and presence of pedestrian crossing on roundabout leg.
- In analysis 2, speeds were measured on a subsample of roundabouts and used to explore its relationship to roundabout geometry. Correlation was found between approach speeds (50 m 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 the necessary speed reduction of vehicles entering the circulatory lane. The analysis also identified the influence of entry radius; 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 of 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 the 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; and
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.

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Author Contributions

Study conception and design: Jan Novák, Jiří Ambros
Data collection: Jan Novák
Analysis and interpretation of results: Jan Novák, Jiří Ambros, Jindřich Frič
Draft manuscript preparation: Jan Novák, Jiří Ambros, Jindřich Frič
All authors reviewed the results and approved the final version of the manuscript.

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