Safety evaluation of Czech roundabouts

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Abstract

Roundabouts around the world are often seen as a beneficial measure for intersection safety. Although their number has grown recently in the Czech Republic, their safety impact has not been fully studied. Furthermore, Czech roundabouts have sometimes been unpopular, including doubts about their benefits. This situation inspired the authors to investigate three questions related to Czech roundabouts: (1) Are roundabouts safer than traditional intersections?; (2) Are roundabout conversions beneficial for safety?; (3) Is Czech roundabout safety performance comparable to other countries? Safety performance functions were developed based on data samples and used in order to answer these research questions. The final results are mixed: roundabouts seem to be safer compared to traditional intersections and before-after study of urban roundabout conversions yielded positive crash modification factors; on the other hand, expected crash frequencies on Czech roundabouts are higher compared to other European countries.

Keywords – roundabout, safety, crash

1. Introduction

In general, the road network consists of intersections and road sections in between. Road users in intersections may change their paths in order to get to their destinations. Therefore, intersections are crucial for the road network mobility performance. However, there is a number of conflict points between road user paths at each intersection. The number is based on the intersection design: while 4-leg intersection features 32 conflict points, a 3-leg has only 9. This is likely to increase the intersection crash performance: according to an international review [1], crash frequencies are in general higher at 4-leg than at 3-leg intersections.

This is why intersections are considered critical elements of the road network and one of the most complex traffic situations that road users encounter [2]. They are places of high crash concentration, despite the relatively short time spent travelling through them [3]. In most countries between 40 and 60% of total crashes occur at intersections [4]. In the Czech Republic the figures from 2013 are as follows:

- 18,549 out of 84,398 crashes occurred at intersections, i.e. approximately 22% of crashes.
- These crashes led to almost 20% of total fatalities (114 out of 583 in total).

In this context, roundabouts around the world are often seen as a beneficial measure. Roundabout is the safest intersection design, mostly thanks to its low number of conflict points, and generally low speed [5].

Several studies have demonstrated roundabout conversion benefits in terms of before-after crash frequency reductions. For example a study of 23 conversions in the US found following reductions: 40% of all crashes, 80% of injury crashes, 90% of fatal crashes [6]. Meta-analysis of 28 studies outside of the US showed 30% to 50% reduction in the number of injury crashes; fatal crashes were reduced by 50% to 70% [7]. (It is to be noted there are also safety disadvantages of specific roundabout designs, such as multilane roundabouts, which may present difficulties for visually impaired users [8] or cyclists [9].)

Since 2000 the number of roundabouts has grown also in the Czech Republic, up to the current number over 1,200. Czech roundabouts are typically unsignalized, located on urban roads (i.e. with speed limit 50 km/h), with 4 legs and a single lane [10]. Their typical diameter is 30 – 40 m, with the lane width of 6 – 7 m, average traffic volume of 12,000 vpd. Some example photographs are presented in Figure 1.

Although roundabout conversions are relatively common in the Czech Republic, their safety impact has not been fully studied. Previous Czech studies were not well designed and based on small samples chosen in a convenient way. For example [11] used cost-benefit analysis with a limited sample of roundabout conversions. Another Czech study [12] assessed the safety of roundabouts using crash prediction models – only using the newly-built ones (not intersections converted to roundabouts which are much more common).

In addition, roundabouts have been sometimes considered unnecessary and unpopular, including doubts about their benefits, even by the Minister of Transport or Czech Police representatives [13]. This controversy and lack of solid knowledge inspired the authors to investigate the following questions related to Czech roundabouts:

1. Are roundabouts safer than traditional intersections?
2. Are roundabout conversions beneficial to safety?
3. Is Czech roundabout safety performance comparable to other countries?

The first two questions are inter-related and they concern two groups of intersections: traditional intersections and roundabouts. The objective of the paper was to answer the research questions. The text is structured in three chapters according to the questions, followed by the final chapter with results and discussion.

2. General intersection comparison

The first question was “Are roundabouts safer than traditional intersections?”. In order to quantify the safety level of both groups, crash prediction models (safety performance functions) were developed and used for comparison.

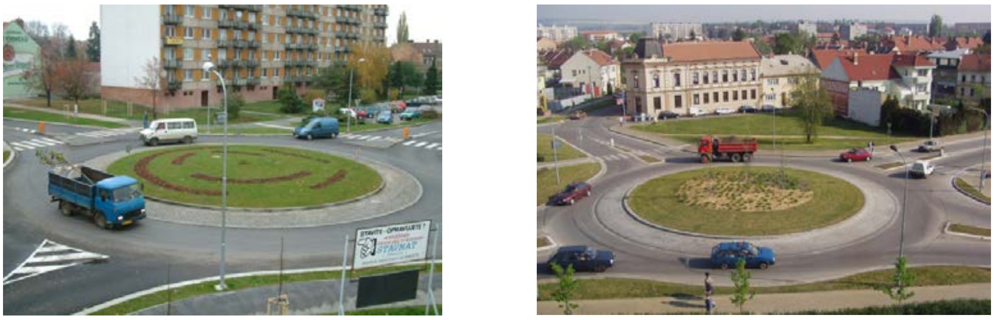

Fig. 1 – Example photographs of typical Czech urban roundabout designs

2.1. Data collection

In the Czech Republic road traffic crashes have been routinely collected by Czech Traffic Police. There are four severity levels: property-damage-only (PDO), slight injury, severe injury, fatal injury. Only the injury crashes (i.e. the sum of crashes with slight, severe or fatal injuries) from an 8-year period (2007 – 2014) were used further. Regarding the traffic volume data, the information from the National Traffic Census 2010 was used.

For comparison, the safety performance functions (SPFs) from comparable environments need to be used for both traditional intersections and roundabouts. Since most of Czech SPFs have been developed in rural safety studies, rural roads were chosen for the following comparison. Three data sets of 4-leg rural intersections were available:

- 39 traditional intersections on regional roads [14]
- 36 traditional intersections on national roads [15]
- 43 roundabouts on national roads [16].

Figure 2 presents the range of traffic volumes of the three samples.

2.2. Safety performance functions

SPFs have been developed for the above mentioned data sets. These equations describe the relation between safety performance (in terms of annual crash frequency) and explanatory variables. All crashes located within 100 m radius were considered intersection-related. In SPFs only traffic volume data (daily sum of entering vehicles) were used as the most influential parameter – this model form is called ‘simple safety performance function’ [17]:

$$crashes/year = \alpha \cdot (sum\ of\ entering\ vehicles)^{\beta} \quad (1)$$

A generalized linear modelling procedure in IBM SPSS 20 statistical software was used, considering the negative binomial data distribution and logarithmic link function. Regression parameters estimates were significant at 95% confidence level. The regression coefficients are summarized in Table 1; Figure 3 presents the SPFs. The functions are displayed in a range of traffic volumes, which is common for all three datasets.

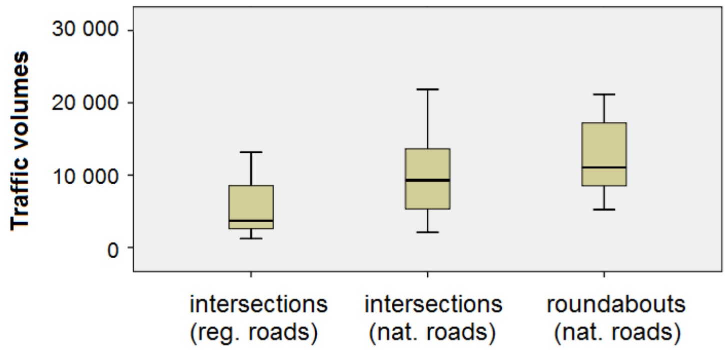

Fig. 2 – Range of traffic volumes in the compared samples of intersection types

Tab. 1 – Regression parameters of SPFs for traditional intersections and roundabouts

Dataset	ln(α)	β
39 intersections on regional roads	-9.936	1.182
36 intersections on national roads	-8.338	0.999
43 roundabouts on national roads	-9.185	0.978

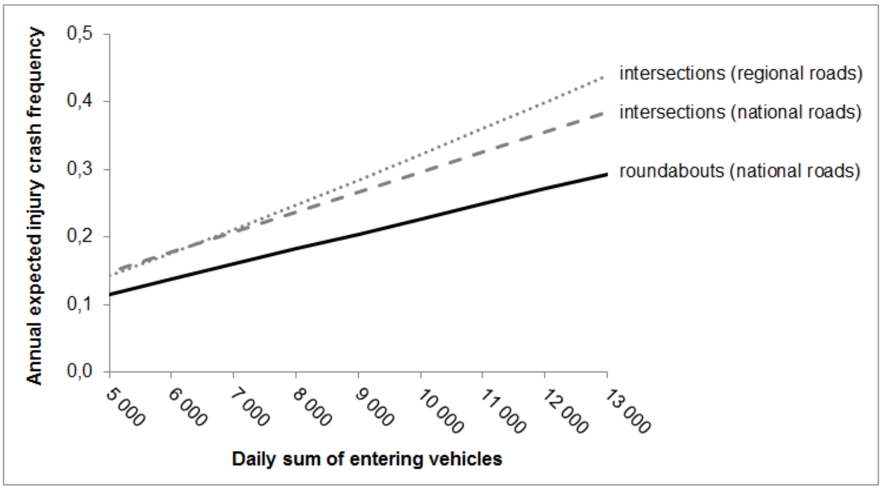

Fig. 3 – Comparison of simple SPFs of samples of traditional intersections and roundabouts

2.3. Comparison

From Figure 3 it is evident that intersections on regional roads are less safe than intersections on national roads; while roundabout SPF has lower values than both traditional intersections SPFs. The probable reasons are as follows:

- National roads are generally of higher quality (road pavement, signing and marking, maintenance, etc.) compared to regional roads. Therefore, intersections on regional roads yield higher crash frequencies than intersections on regional roads.
- Roundabouts are generally safer compared to traditional intersections.

3. Safety effectiveness of roundabout conversions

The second question was “Are roundabout conversions beneficial to safety?”. In order to quantify the safety effectiveness its crash modification factor has been calculated.

3.1. Methodology

Crash modification factor (CMF) is a multiplicative factor used for calculating the expected number of crashes after implementing safety measures at a specific site (roundabout conversion), through multiplication with expected crash frequency without treatment [18]. A CMF value higher than 1.0 indicates an expected increase in crashes, while a value lower than 1.0 indicates an expected reduction in crashes after the conversion.

In general, several methodologies may be used in order to obtain CMF values. Before-after methodology, with empirical Bayes adjustment (in short "EB approach"), has been deemed the most suitable. The method corrects for regression to the mean and other confounding factors [19-21].

In the EB approach, the change in safety for a site is given by [6, 22, 23]:

$$\theta = \frac{\lambda}{\pi} \tag{2}$$

where π is the expected number of crashes that would have occurred in the after period without conversion (reference group) and λ is the number of reported crashes in the after period. In estimating π, the effects of confounding factors explicitly accounted for by estimating safety performance functions (SPF). At first, SPF is used to estimate the number of crashes that would be expected each year of the before period at locations with traffic volumes similar to the one being analyzed. The sum of these annual SPF estimates (P) is then combined with the number of crashes (x) in the n years before the conversion in order to obtain an estimate of the expected number of crashes (m) before conversion:

$$m = w_1 \cdot x + w_2 \cdot P \tag{3}$$

where the weights w_1 and w_2 are estimated from the mean and the variance of the SPF estimate as

$$w_1 = \frac{P}{k + n \cdot P} \tag{4}$$

$$w_2 = \frac{k}{k + n \cdot P} \tag{5}$$

where k is a constant for a given model (overdispersion parameter) and is estimated during the SPF calibration process with the use of a maximum likelihood procedure [6]. Both weights are complementary and their sum equals 1.

The factor R is then applied to m to account for the length of the after period and differences in traffic volumes between the before and the after periods. This factor is the sum of the annual SPF predictions for the after period divided by P, the sum of these predictions for the before period. The result, after applying this factor, is an estimate of π. It is then summed over all sites in a group of roundabout conversions (to obtain π_{sum}) and compared with the number of crashes during the after period in that group (λ_{sum}). The variances of π_{sum} and λ_{sum} are also calculated and summed over all sites in the group of converted roundabouts. [6]

The crash modification factor (or index of effectiveness) θ and its standard deviation (SD) is estimated as:

$$\theta = \left(\frac{\lambda_{sum}}{\pi_{sum}}\right) \Big/ \left(1 + \frac{var(\pi_{sum})}{\pi_{sum}^2}\right) \tag{6}$$

$$SD(\theta) = \sqrt{var(\theta)} = \sqrt{\theta^2 \left(\frac{var(\lambda_{sum})}{\lambda_{sum}^2} + \frac{var(\pi_{sum})}{\pi_{sum}^2}\right) \Big/ \left(1 + \frac{var(\pi_{sum})}{\pi_{sum}^2}\right)^2} \tag{7}$$

The percentage change in crashes is then calculated as $100 \cdot (1 - \theta)$ [6].

3.2. Data and calculation

As already mentioned, the most typical Czech roundabout layout is: urban roads, unsignalized, 4 legs, single lane. Therefore, such roundabout conversions were chosen for the study as a treatment group. In order to locate the converted roundabouts, the data from the entire Czech road network were used. 202 cases were identified – however, this sample had to be reduced only to cases where traffic volume and crash data were available – this reduction resulted in 18 cases. Crash frequencies and traffic data (sum of entering vehicles) were assigned to them. For descriptive characteristics see Table 2.

Intersections of the same design as the treatment group, but not converted into roundabouts, were used as a reference group. Again, the same filters had to be applied (traffic volume and crash data availability) and 66 cases were identified. Crash frequencies and traffic volume (sum of entering vehicles) were assigned to them. A data period of 18 years (1995 – 2012) was used (see Table 3).

The distribution of traffic volumes in treatment and reference groups are not completely equal, and overlap to some extent: maximal values are approx. 27,000 and 21,000 in treatment group (before conversion) and reference group (without conversion) respectively. Maximum of 40 total crashes is equal for both groups.

In order to test the necessary compatibility of both groups, the consistency of their trends was tested using time series sample odds ratios and confidence interval according to [19]. The calculated 95% confidence interval included the value of 1 as requested, with average of odds ratios equal to 1.02 – therefore, the reference group is deemed suitable.

A simple safety performance function was fitted to reference group data, of the form similar to Equation (1) – see Table 4.

Tab. 2 – Characteristics of 18 studied roundabout conversions with before (B) and after (A) data

Location	*Year opened*	*Sum of entering vehicles*		*Years of data*		*Total crashes*		*Injury crashes*	
		B	*A*	*B*	*A*	*B*	*A*	*B*	*A*
Hrabačov	2009	11,729	11,417	9	3	17	1	14	1
Karviná	2005	17,632	21,039	7	7	12	7	11	6
Lanškroun	2003	9,182	13,657	5	9	3	11	2	11
Lázně Bohdaneč	2003	11,073	17,348	8	9	13	7	9	6
Letovice	2007	11,506	12,112	12	5	13	0	11	0
Moravská Třebová	2003	12,807	13,773	8	9	11	4	8	3
Náchod 1	2003	15,168	21,588	4	9	6	6	5	5
Náchod 2	2003	26,971	21,760	5	9	3	9	3	8
Orlová	2003	9,851	11,432	2	9	0	2	0	2
Rokycany	2004	11,753	16,341	9	8	10	2	6	2
Rožmitál p. Třem.	2003	4,957	5,821	8	9	1	1	0	1
Šenov	2004	8,337	9,555	9	8	19	3	14	1
Třeboň	2002	13,576	16,325	7	10	3	11	12	8
Valašské Meziříčí 1	2002	17,091	21,593	1	10	1	5	0	3
Valašské Meziříčí 2	2002	22,868	34,845	1	10	1	4	1	3
Vrchlabí	2005	10,245	10,340	10	7	23	7	18	4
Vsetín	2003	11,363	13,431	5	8	2	4	2	4
Zábřeh	2009	14,682	11,745	14	3	40	0	32	0

Tab. 3 – Descriptive parameters of 66 intersections in the reference group

Variable	*Minimum*	*Maximum*	*Mean*	*Sum*
Sum of entering vehicles	898	21,384	6,957	459,182
Injury crashes	0	22	7	484
Total crashes	0	40	10	686

Tab. 4 – Parameters of reference group SPFs: regression coefficients α and β, overdispersion parameter k, with their standard errors (S.E.)

Crash severity	$ln(\alpha)$ *(S.E.)*	β *(S.E.)*	k *(S.E.)*
Total crashes	-2.998 (1.050)	0.609 (0.120)	0.357 (0.080)
Injury crashes	-3.278 (1.112)	0.602 (0.127)	0.352 (0.088)

Tab. 5 – Excerpt of data from Table 2

Location	*Sum of entering vehicles*		*Years of data (n)*		*Total crashes (x)*	
	B	*A*	*B*	*A*	*B*	*A*
Vrchlabí	10,245	10,340	10	7	23	7

The resulting expected (predicted) crash frequency estimates were adjusted via empirical Bayes method, according to Equations (3) – (5).

3.3. Worked example

In order to demonstrate the application of the described methodology, a worked example for safety effectiveness in terms of total crashes for a roundabout in Vrchlabí will be presented. The following required data were excerpted from Table 2 (Table 5):

The calculation steps were applied as follows:

- Predicted crash frequency (based on Equation (1), with parameters α, β from Table 4): $P\ (crashes\ in\ 18\ years) = \exp(-2.998) \cdot (sum\ of\ entering\ vehicles)^{0.609}$, i.e.:
    - in the before period: $P_B = \frac{\exp(-2.998) \cdot 10{,}245^{0.609}}{18} = 0.768$ crashes per year
    - in the after period: $P_A = \frac{\exp(-2.998) \cdot 10{,}340^{0.609}}{18} = 0.772$ crashes per year
- Expected crash frequency "before" (based on Equations (3) – (5)):
$$m_B = \frac{P_B \cdot x}{k + n_B \cdot P_B} + \frac{k \cdot P_B}{k + n_B \cdot P_B} = \frac{0.768 \cdot 23}{0.357 + 10 \cdot 0.768} + \frac{0.357 \cdot 0.768}{0.357 + 10 \cdot 0.768} = 2.232$$
- Expected crash frequency "after": $m_A = R \cdot m_B = \frac{0.772}{0.768} \cdot 2.232 = 1.006 \cdot 2.232 = 2.244$
- The number of crashes that would have occurred in the after period had the conversion not taken place: $\pi = m_A \cdot n_A = 2.244 \cdot 7 = 15.711$. The variance of π is given by [6]: $var(\pi) = m_B \cdot \frac{(R \cdot n_A)^2}{\frac{k}{P_B} + n_B} = 2.232 \cdot \frac{(1.006 \cdot 7)^2}{\frac{0.357}{0.768} + 10} = 10.568$

The same procedure was applied for injury crashes. After the calculation for each roundabout, individual results were summed and used in Equations (6) – (7) to obtain the safety effectiveness.

3.4. Safety effectiveness

The results are reported for total crashes and injury crashes. The values are in the form of crash modification factor (CMF) and percentages of crash frequency reduction – see Table 6. Mean values are accompanied with standard deviations (S.D.) and confidence intervals, computed using 95% confidence level (i.e. cumulative probability 1.96) as follows [18]:

$$95\%\ confidence\ interval = mean \pm 1.96 \cdot (standard\ deviation) \quad (8)$$

Tab. 6 – Crash modification factors (mean and standard deviation) and corresponding crash reductions, both with confidence intervals

	Crash modification factor θ		*Crash reduction* $100 \cdot (1 - \theta)$	
Crash severity	*Mean (S.D.)*	*Confidence interval*	*Mean*	*Confidence interval*
Total crashes	0.48 (0.08)	0.33 – 0.63	52%	37% – 67%
Injury crashes	0.47 (0.08)	0.32 – 0.63	53%	37% – 68%

The results are positive and significant (the confidence interval do not include zero). Crash reduction values of 52% and 53% are relatively consistent with previous studies – for example meta-analysis of non-U.S. studies Elvik [7] reported crash reductions for 4-leg unsignalized roundabout conversions approx. between 50% and 60%.

4. International comparison of roundabout safety

The third question was "Is Czech roundabout safety performance comparable to other countries?". In this regards illustrative international comparison was made, using simple safety performance functions (SPF).

In line with the previous analyses, only 4-leg single lane roundabouts, as a typical Czech roundabout design type, were selected. In total 196 roundabouts were used for Czech SPF (for details see [16]). The Czech SPF was compared to several other SPFs that were retrieved from international literature [9, 24-28]. They included European examples (Belgium, France, Italy, Sweden, United Kingdom) as well as United States, Canada and New Zealand – see Figure 4. The range of AADT values is limited between 1,000 and 30,000 vehicles per day. SPF parameters are listed in Table 7.

Considering the shape of curves, several conclusions may be made:

- Traditionally safe countries (Sweden, New Zealand) have the lowest expected crash frequencies.
- North American countries (United States and Canada) have similar shapes on the other side of the range.
- Most European countries (Belgium, United Kingdom, Italy) have values between those two thresholds.

Compared to North American SPFs Czech crash frequencies are higher at lower AADT and lower at higher AADT (the threshold is between 10,000 and 15,000 vehicles per day).

Tab. 7 – Regression parameters of international roundabout SPFs ($crashes/year = \alpha \cdot AADT^{\beta}$)

Country and source	α	β
Belgium [9]	$1.10 \cdot 10^{-4}$	1.00
Canada [28]	$3.05 \cdot 10^{-6}$	1.42
Czech Republic [16]	$4.65 \cdot 10^{-2}$	0.43
France [28]	$2.40 \cdot 10^{-7}$	1.40
Italy [26]	$1.15 \cdot 10^{-8}$	1.86
New Zealand [27]	$6.11 \cdot 10^{-4}$	0.58
United Kingdom [24]	$8.00 \cdot 10^{-6}$	1.24
United States [25]	$2.30 \cdot 10^{-3}$	0.75
Sweden [28]	$3.08 \cdot 10^{-6}$	1.20

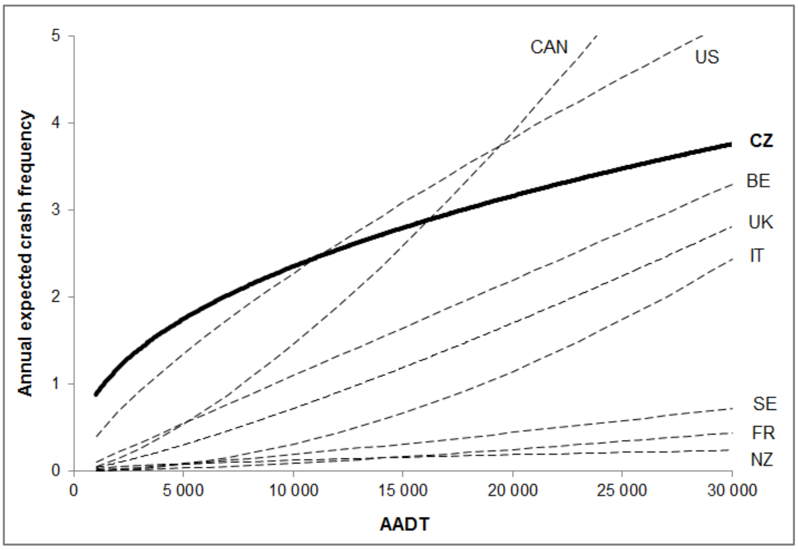

Fig. 4 – Comparison of Czech roundabout SPF (CZ) with international SPFs (BE – Belgium, CAN – Canada, FR – France, IT – Italy, NZ – New Zealand, UK – United Kingdom, US – United States, SE – Sweden)

However, compared to other European countries (and New Zealand) Czech SPF performs worse in the whole range of AADT values.

5. Results and discussion

Three research questions were stated in the introduction:

(1) Are roundabouts safer than traditional intersections?;
(2) Are roundabout conversions beneficial for safety?;
(3) Is Czech roundabout safety performance comparable to other countries?

The paper provided the information and analyses in order to answer these questions. The results are mixed – two answers are positive and one is negative:

- Answer to the first question: Crash frequencies on roundabouts are lower compared to traditional intersections.
- Answer to the second question: Roundabout conversions before-after study yielded positive crash modification factors.
- Answer to the third question: Czech roundabout expected crash frequencies are higher compared to other European countries.

However, considering the international comparison of roundabout SPFs the reasons for the differences may be numerous; some of them are listed (for more see [28]):

- Various crash reporting practices. Most countries report just injury crashes and the data in the graph reflect this fact. They should have therefore lower values compared to the Czech SPF, which also uses property damage only crashes. However, there are differences with crash reporting among specific countries as well: e.g. in Sweden and New Zealand approximately 40% of injury crashes are reported, while in United States it is 70% and even 100% in Italy [28].

- Definition of intersection crashes. There is no uniform criterion used for assigning a crash to an intersection. For example, Belgian practice is to consider all crashes within an area of 100 m (the same criterion was used for Czech data). However, in Canada 20 m limit is used, 30 m in Sweden and 50 m in New Zealand [28].
- Design and traffic differences. For example, roundabouts in France have a long tradition; what is more, they were built there primarily for safety reasons. On the contrary, the United States and the United Kingdom use roundabouts mainly because of capacity. These underlying concepts dictate the roundabout design, e.g. the diameter [24]. There are also international differences in the age of roundabouts and the data sets do not cover the same time periods or rural/urban areas. In addition, speed characteristics and climatic conditions may be significantly different.

To sum up, the safety level of roundabouts may be deemed sufficient in the Czech context: they are generally safer than traditional intersections, considering both the newly built and roundabout conversions. From this point of view there is no reason to limit the increasing trend of roundabout construction.

Regarding international SPF comparison, several potential biases were mentioned (e.g. differences in crash reporting or crash definitions), therefore, the results should not be considered definite. Nevertheless, the Czech SPF has apparently higher values of crash frequencies – it is likely that Czech roundabout safety performance lags behind several other European countries.

Although several methodological weaknesses in this comparison were mentioned, this finding is consistent with the general knowledge: Czech traffic is not sufficiently safe in the European context and there is a potential for improvement. One of possible directions may be to increase safety situation on Czech roundabouts, as indicated in the paper. Further study improvements may focus on specific design/geometry risk factors and related crash types and patterns [29-31]. For example, importance of deflection (i.e. amount of trajectory changes imposed by roundabout geometry) is often overlooked: it is mentioned in Czech roundabout design guidelines, but without any specific guidance. It should therefore be considered in future roundabout safety modelling and analyses.

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