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Evaluation of safety effect of turbo-roundabout lane dividers using floating car data and video observation

Mariusz Kieć[a,*], Jiří Ambros[b], Radosław Bąk[a], Ondřej Gogolín[b]

[a] Cracow University of Technology, Warszawska 24, 31-155 Kraków, Poland
[b] CDV – Transport Research Centre, Líšeňská 33a, 636 00 Brno, Czech Republic

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ABSTRACT

Roundabouts are one of the safest types of intersections. However, the needs to meet the requirements of operation, capacity, traffic organization and surrounding development lead to a variety of design solutions. One of such alternatives are turbo-roundabouts, which simplify drivers' decision making, limit lane changing in the roundabout, and induce low driving speed thanks to raised lane dividers. However, in spite of their generally positive reception, the safety impact of turbo-roundabouts has not been sufficiently studied. Given the low number of existing turbo-roundabouts and the statistical rarity of accident occurrence, the prevalent previously conducted studies applied only simple before-after designs or relied on traffic conflicts in micro-simulations. Nevertheless, the presence of raised lane dividers is acknowledged as an important feature of well performing and safe turbo-roundabouts.

Following the previous Polish studies, the primary objective of the present study was assessment of influence of presence of lane dividers on road safety and developing a reliable and valid surrogate safety measure based on field data, which will circumvent the limitations of accident data or micro-simulations. The secondary objective was using the developed surrogate safety measure to assess and compare the safety levels of Polish turbo-roundabout samples with and without raised lane dividers.

The surrogate safety measure was based on speed and lane behaviour. Speed was obtained from video observations and floating car data, which enabled the construction of representative speed profiles. Lane behaviour data was gathered from video observations.

The collection of the data allowed for a relative validation of the method by comparing the safety performance of turbo-roundabouts with and without raised lane dividers. In the end, the surrogate measure was applied for evaluation of safety levels and enhancement of the existing safety performance functions, which combine traffic volumes, and speeds as a function of radii). The final models may help quantify the safety impact of different turbo-roundabout solutions.

1. Introduction

Intersections are crucial elements, which influence the operation and efficiency of traffic in the road network. However, providing safety is one of the most important design purposes, and for this reason many specific criteria need to be taken into account. One of the safest type of intersection is a single-lane roundabout. Despite the numerous benefits of this type of intersections, their application is not always justified or possible, for example in cases of intersection of multi-lane roads or the reduction in intersection capacity. Multi-lane roundabouts provide higher capacity, however they significantly outnumber single-lane roundabouts in terms of the number of registered collisions. The geometric layout of such an intersection results in higher speed, more frequent lane-changing manoeuvres, as well as higher number of potential collision points, including the crossing of traffic flows. The need to satisfy safety requirements and traffic performance, traffic organization and management has led to the application of different circular intersection solutions.

The solution, offering a compromise between safety and higher capacity, is turbo-roundabouts, which were first applied in the Netherlands. Also in Poland turbo-roundabouts are beginning to be used more and more often, even though there are no uniform regulations for their geometric design, traffic organization and traffic performance analysis. In most cases they are designed based on guidelines from the Netherlands. This lack of clear design guidelines leads to different turbo-roundabout solutions. These often differ significantly

* Corresponding author.
E-mail addresses: mkiec@pk.edu.pl (M. Kieć), jiri.ambros@cdv.cz (J. Ambros), rbak@pk.edu.pl (R. Bąk), ondrej.gogolin@cdv.cz (O. Gogolín).

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one from another, while displaying a number of characteristic features typical of the Dutch solutions (Fortuijn, 2009; Ministry of Transport, 2009). One of the features, which differentiate such intersections, is the method of separation the traffic lanes in the circulatory roadway and/or entries into the roundabout, which can have a considerable influence on road safety and winter maintenance, as well as drivers' behaviour.

Following the previous Polish studies, the primary objective of the paper is to assess the influence of presence of lane dividers on road safety and develop a reliable and valid surrogate safety measure based on the field data, which will circumvent the limitations of accident data or micro-simulations. The secondary objective is to define a surrogate safety measure to assess and compare safety levels of Polish turbo-roundabouts with and without raised lane dividers and various geometrical parameters at the turbo-roundabouts.

After the literature review, methods are presented, followed by analysis, results, discussion and conclusions.

2. Literature review

Turbo-roundabouts are the solution which, being an alternative to multi-lane roundabouts, helps to simplify the process of drivers' decision making, limit lane changing and reduce the number of collision points, as well as induce low driving speed (Guerrieri et al., 2018). As a result, turbo-roundabouts are generally well-received and applied more and more often around the world.

These benefits are obtained mainly due to a specific feature: physical lane dividers. Since in multi-lane roundabouts, a part of drivers (estimated up to 40% by Kociánová, 2017) are tempted to cut in the curves at low traffic volumes, the raised lane dividers help curb this behaviour (Fortuijn, 2009). The dividers thus eliminate conflict points caused by weaving manoeuvers, and lead to speed reduction because of increased deflection. On the negative side, raised curbs make snow removal difficult and may present a risk for motorcyclists (Vasconcelos et al., 2014). This is why application of lane dividers varies from country to country. For example, in Germany (Brilon, 2014) lane dividers are not accepted due to the mentioned concerns; similar reasons were reported in the Czech Republic (Škvain et al., 2017). According to Tollazzi (2015) and Džambas et al. (2017), the lane dividers are used on turbo-roundabouts in the Netherlands, Hungary and former Yugoslav republics (Slovenia, Macedonia, Croatia, Serbia); while only lane marking is instead used in Germany, Denmark and the Czech Republic. In Poland both approaches (with and without dividers) are used (Macioszek, 2015; Chodur and Bąk, 2016).

It should be also noted that height of lane dividers is different across countries. The original Dutch research (Fortuijn, 2009) recommended 7 cm as optimal, and this height is also applied in design manuals in post-Yugoslav republics. On the other hand, guidelines in other countries list different values, such as 4 cm or 5 cm (BUT, 2015; Ministry of Transport, 2015). In Poland the height of lane dividers varies between 6 and 12 cm. In addition, various materials may be used for lane dividers (Petrů et al., 2016).

While turbo-roundabouts are generally acknowledged as a safe solution, it is difficult to estimate the potential for reducing accidents, compared to other types of intersections. Previous studies (Fortuijn, 2009; Brilon and Geppert, 2014; Vos, 2016) applied only naive before-after designs or relied on traffic conflicts in micro-simulations (Kociánová, 2017; Mauro et al., 2015; Bulla-Cruz et al., 2016). The results of the before-after analysis carried out in the Netherlands (Fortuijn, 2009) indicated that the potential for reducing accidents is close to that of single-lane roundabouts, i.e. approx. 75%.

Using a developed model for the potential accident rate evaluation, Mauro and Cattani (2010) determined that the level of risk for traffic safety expressed in the number of accidents is lower by approx. 25–30%, whereas for traffic events less frequent by 40–50% compared to multi-lane roundabouts. However, the authors emphasised that the results were obtained based on an extension of the theoretical model of multi-lane roundabouts onto turbo-roundabouts, but without calibration, so the calculations may be prone to errors.

In Poland, an attempt was made to assess the influence of raised lane dividers on traffic safety based on the available data on registered accidents (Macioszek, 2015). One of the conclusions indicated that the level of traffic safety at turbo-roundabouts without a physical lane separation is similar to that of multi-lane roundabouts, whereas the application of raised lane dividers increases the level of safety. However, the results may have been biased by a small sample and a naive before-after study design.

To sum up, the studies were usually limited by small numbers of turbo-roundabouts (and accidents), the short before-after time periods, as well as incomplete registration of property damage only accidents. Therefore some studies attempted using surrogate safety measures. Such assessment measures include incorrect behaviours of drivers as well as the speed of vehicles. The studies considered speed as a factor influencing the level of traffic safety on intersections with a circular roadway. Some studies also considered speed among explanatory variables when developing accident prediction models (safety performance functions, SPFs) – for example (Turner et al., 2009; Chen et al., 2011; Chen et al., 2013) used average speed of vehicles in the roundabout roadway and found its statistically significant relationship to accident frequencies.

The results of the studies suggest that the available theoretical speed of vehicles in the roundabout is strictly connected to its type and geometry (Fig. 1). It should be observed that, in general comparison, the speed of vehicles at single-lane roundabouts, is similar to the speed on turbo-roundabouts (Fortuijn, 2009). The presented relation implies a significant influence of the radius of curves on speed. As a result, the value of speed at turbo-roundabouts indirectly depends on the number of lanes, raised lane dividers and directly on the value of curvature of the movement trajectory. It should be noted that in the event of turbo-roundabouts the value of radii of curvature is variable and difficult to estimate (because of changing of radii), which is due to the specific nature of the design of turbo-roundabouts.

Based on the problems, mentioned in introduction and literature review, the following gaps in the knowledge are indicated:

- lack of impact assessment of lane dividers presence on road safety
- lack of road safety assessment for various scenarios of turbo-roundabouts, with different geometrical parameters, traffic organization, which can be assessed based on speed profile.

3. Methods

In order to fill the gaps, Authors decided to investigate the safety impact of lane dividers through safety performance functions (SPFs) with surrogate safety measures. Based on data about presence of lane dividers and speed profiles, SPFs were developed. The surrogate safety measure consisted of road users' interactions, which involved speed and lane behaviour. Speed and lane behaviour were obtained from video

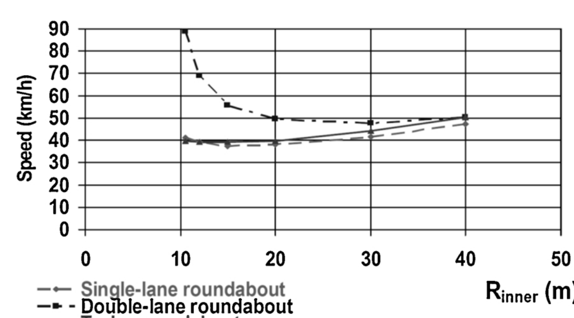

Fig. 1. The impact of the type of a circular intersection on the vehicle speed (Fortuijn, 2009).

recording and floating car data, which enabled the construction of representative speed profiles.

3.1. Safety performance function

The main objective of the study was to develop a SPF based on data about presence of lane dividers and speed profiles. SPF was expected to show the impact of lane dividers and changes in speed on accidents (injury accidents and PDO – property damage only).

Consistently with literature review (Turner et al., 2009; Chen et al., 2011; Chen et al., 2013; Ambros et al., 2016; Novák et al., 2018), the basic form of SPF was adopted, including exposure variable (AADT) and explanatory variables: presence of lane dividers (Yes/No) or speed profile data. For speed profile data different values. i.e. speed at entry, exit, on the circulatory roadway and average speed through turbo-roundabouts were tested (see Section 3.2).

To estimate the predicted accident frequency rate *Acc*, SPF was calibrated using the mentioned variables. A following GLM regression model taking into account Negative Binomial error distribution, was used:

$$Acc = \exp(\alpha)\bullet AADT^{\beta}\bullet\exp(\gamma\bullet x_i) \tag{1}$$

where:

Acc is the predicted average annual accident frequency;

AADT is the annual average daily traffic flow [veh/day];

x_i are other explanatory variables (presence of lane dividers *Div* or speed *S*);

α, β, γ regression parameters.

The variables were kept in the model, if their influence was statistically significant with p-value at least 0.1 (90% level of confidence).

The obtained regression parameters may be used to estimate the average Accident Rate (AR_{div}) for presence of lane dividers based on the following Eq. (2):

$$\mathrm{AR_{div}} = \exp(\gamma) \tag{2}$$

where:

γ is the regression parameter estimate related to the presence of lane dividers from Eq. (1)

3.2. Speed as a surrogate safety measure

The main objective of the speed research carried out on the analysed roundabouts was to indicate a relationship between the geometry of intersections and the speed of a vehicle passing through a turbo-roundabout. For this reason, two data sources were used:

- video monitoring of speed in cross-sections and drivers' behaviours,
- results of floating car data (FCD) for selected polygons based on speed, time, longitude and latitude data from GPS

Speed was estimated based on video observation and registering time of passing specific cross-sections (Fig. 3). Studies using the GPS technology were carried out to help collect data about speed profiles for passing a turbo-roundabout and the trajectory of this passing. Based on the above-mentioned methods, drivers' behaviour was assessed both in roundabouts with and without lane dividers. Results of speed analyses were used to evaluate relative changes in road safety based on existing SPFs in which speed is included as a variable.

The traffic analysis using video recording was carried out at a sample of Polish turbo-roundabouts located on urban roads with the speed limit 50 km/h. The analysis included 12 research sites with different configuration of turbo-roundabouts (number of entries, number of lanes at the entry, exit and circulatory roadway), including 7 with raised physical dividers. Table 1 presents minimum, maximum, average and modal values for analysed turbo-roundabouts. Fig. 2 shows examples of research sites without lane dividers (a) and with lane dividers (b). Each measurement lasted approximately 5 h.

Table 1
Geometrical Parameters of Analyzed Turbo Roundabouts.

	min	max	average	modal value
width of inner/outer lane in the roundabout [m]	5.0	5.5	5.1	5.0
outer diameter [m]	48.0	72.0	57.3	60.0
inner diameter [m]	22.0	44.0	31.4	32.0
entry width [m]	7.0	7.8	7.3	7.0
entry radius [m]	12.0	20.0	16.4	17.0
trajectory staggering to the approach axis inner lane [m]	5.0	18.8	12.2	17.3
trajectory staggering to the approach axis outer lane [m]	8.5	21.5	13.9	19.0

The research using the FCD technology was carried out on 4 roundabouts, including 2 with physical dividers. The measurement included vehicles passing at least 20 times straight through the roundabout in both directions. In total, results were obtained for 100 tracks of vehicles passing the roundabout.

Traffic observations were conducted using a mast on which a set for video recording was mounted. This set consisted of three cameras mounted on a jib with a freely adjustable angle and height of the recording devices. Cameras were set in such a way that their scope covered the longest possible section of the roundabout, including sections preceding and following the analysed intersection (Fig. 3). This allowed to designate sections in the roundabout which were used to measure the following speeds: approach, entry, circulatory and exit, which were later used to develop speed profiles for passing through the roundabout. The geometry of roundabout has been verified based on obtained Cad projects.

The studies with FCD technology have been carried out using high frequency GPS recorder and were aimed at collecting data about the flow of vehicles in the roundabout and on the approach to the roundabout. The studies included the registration of data on the position of the vehicle and its speed with 10 Hz frequency (each 0.1 s). The precision of this procedure was sufficient enough to render the detailed trajectory of the analysed vehicle. A test vehicle followed the analysed vehicle at a constant gap, registering indirectly its trajectory and speed. This made it possible to register a driver's random behaviour on roundabouts.

The data about the position of the vehicle in motion was used to recreate its trajectory in AutoCad civil 3D (Fig. 4). Based on this, the actual values of the radii of curves were determined automatically in AutoCad civil 3D software with, based on longitude and latitude data from GPS, and values of the registered speed were attributed to them, thus creating speed profiles. To verify location of measurement cross-sections Cad projects were used.

Based on video recording and floating car data, speed models were developed for: entry, circulatory and exit sections separately and for passing through roundabout. Model predicting average speed *AS* through roundabout was developed through the OLS regression approach, as typically used in speed modelling (TRB, 2011).

Predicted value of *AS* was used as a surrogate safety measure to calculate relatively impact of different scenarios for turbo-roundabouts on road safety. To this end, authors applied the existing accident prediction models for roundabouts, which take into account speed as an independent variable.

a) NZ (New Zealand) model (Turner et al., 2009)

$$Acc = 6.12\bullet 10^{-8}\bullet Q_e^{0.47}\bullet Q_c^{0.26}\bullet S_C^{2.13} \tag{3}$$

b) US model (Chen et al., 2013)

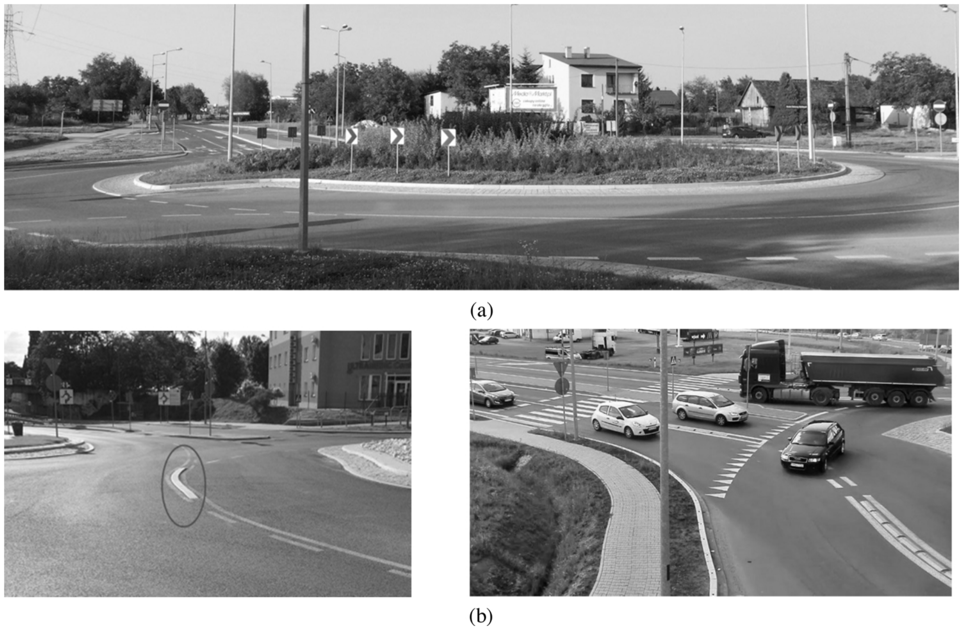

Fig. 2. Examples of research sites without lane dividers (a) and with different height of lane dividers (b).

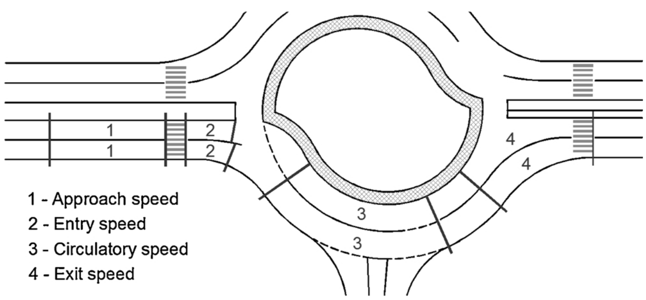

Fig. 3. Layout of measurement speed sections: 1 – approach (S_{app}), *2 – entry (S_{en}), 3 – circulatory roadway (S_{cir}), 4 – exit (S_{ex}).*

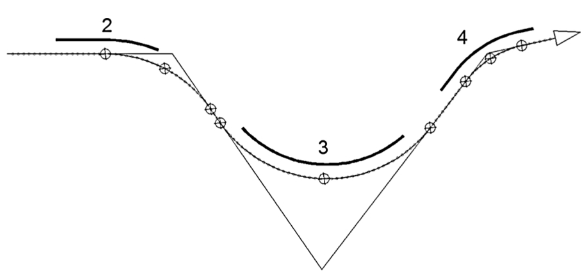

Fig. 4. Example of matching trajectory in AutoCad Civil 3D.

$$Acc = 7.7 \bullet 10^{-8} \bullet AADT^{0.5094} \bullet AAS_{predicted}{}^{4.3314} \quad (4)$$

c) IT (Italian) model (Chen et al., 2013)

$$Acc = 1.5 \bullet 10^{-13} \bullet AADT^{2.8623} \bullet AAS_{predicted}{}^{0.6339} \quad (5)$$

where: Acc = annual number of accidents, Q_e = entering flow on the approach, Q_C = circulating flow, S_C = average free-flow speed of circulating vehicles as they pass the approach being modelled [km/h], $AADT$ = annual average daily traffic, $AAS_{predicted}$ = approach average predicted speed for single roundabout [Mph]

As a second surrogate safety measure incorrect behaviour based on the video recording on turbo-roundabouts was identified, among others:

- driving over the edge of the lane (separately for inner and outer lanes, cutting the curves),
- deliberate changing of traffic lanes which is not a result of wrong lane selection at entry.

4. Analysis and results

4.1. Safety performance function

SPF was developed based on available accident data from 9 turbo-roundabouts and speed data presented in Section 4.2. Table 2 shows the information available for each turbo-roundabouts with a statistical summary of accidents data set.

In the SPF, apart AADT, presence of dividers or average speed calculated based on Eqs. (9) and (10) were considered separately. Only SPF with binary variable, presence of lane dividers was statistically significant. Results are shown in Table 3. SPF with speed as an explanatory variable, instead of presence of lane dividers, was statistically insignificant with p-value higher than 0.1 for AADT and speed variables. Therefore this model is not presented.

Comparison of average yearly observed and predicted accidents and PDO accidents for 9 turbo-roundabouts indicates that the coefficient of determination (R^2), used in ordinary least-squares regression, is equal to 0.777 and 0.875 respectively (Fig. 5).

Effects of binary variable is to be interpreted in comparison to the reference category, i.e., scenario with lane dividers (with zero regression coefficient). In Table 3, parameters of *Div* (lane dividers) were reported for category “no dividers”. Therefore the effect approximately equals to exponential value of 0.5 = exp(0.5) = 1.6. This illustrates that lack of lane dividers is associated with an increase in the average

Table 2
Summary Statistics of Accidents Data Used in the Elaboration.

Variable	Abbrev.	Number of records	Min	Max	Mean	Std. Dev.
Lane dividers	*Div*	20 (Yes) 16 (No)				
Annual average daily traffic	*AADT*		5000	26530	16886.06	6572.55
Accidents/year			0	9	2.89	2.67

Table 3
Values of SPF regression parameters, standard errors and p-values.

Parameter	Estimate	Std. Error	Significance
accidents			
Intercept	−7.707	3.342	0.021
ln *AADT*	0.884	0.347	0.011
Div	0.461	0.280	0.100
Dispersion	0.223	0.159	
PDO (property damage only) accidents			
Intercept	−7.369	3.340	0.027
ln *AADT*	0.841	0.347	0.015
Div	0.492	0.280	0.079
Dispersion	0.200	0.157	

annually number of accidents (specifically 1.59 for accidents and 1.64 for PDO accidents). This results indicates significant positive impact of presence of lane divider. This impact is similar to results of US model (Chen et al., 2013) based on average speed for single roundabouts presented in Section 4.2 (Fig. 9). Unfortunately it was not possible to assess impact of speed on turbo-roundabouts on accidents based on regression model.

4.2. Speed as a surrogate safety measure

The analysis of the results which were obtained enabled the estimation of the average speed of vehicles S_A, the standard deviation *Stddev* and S_{15} and S_{85} quantile for vehicles in free flow (Table 4, Fig. 6) for the following sections of the roundabout, described in Section 2. In the Fig. 6 also values of average speed and plus and mines values of standards deviations (S_{av}+*Stddev*, S_{av}-*Stddev*) are presented to show of speed variability.

The results presented in Table 4 concern correct passages through the turbo-roundabout both in the case of the presence of lane dividers and their absence. Incorrect passages were discarded and analysed independently. The highest values of speed occurred at the approach to the roundabout, whereas the lowest – in the circulatory roadway. The speed at the entry and exit remained similar (speed change up to 1%) and suggested that a major factor affecting the speed value is the geometric solution.

The comparison of the vehicle speed in the lanes indicates higher speeds at the approach to the turbo-roundabout in the left lane (in the case of multi-lane entries), which was an expected result due to drivers' propensity to drive fast when in the left lane. Greater differences in speeds depend on the combination of the higher approach speed and values of radii for entry and circulatory roadway, because of smaller radius.

The speed values for lanes in the circulatory roadway *Scir* differ one from another to a greater extent (by more than 5%) than in the case of entries and exits. The vehicles in an inner lane cover the route with a radius that is lower by at least a few metres than in the case of vehicles moving in the outer lane, which translates into the difference in speed.

The values of standard deviation (Table 4) and cumulative speed distribution functions (Fig. 6) for the subsequent sections indicate a greater dispersion of speed on:

- the approach to the roundabout, which is affected by external factors (road and its surroundings)
- at the entry of the roundabout, where the approach speed is still significant factor as well as radii of entries

For the two remaining sections the dispersion of speed is comparable.

The next step of the empirical research involved comparing the behaviour of drivers passing through the roundabout without lane dividers correctly and incorrectly. The incorrect behaviours made up approx. one third of all the passages observed. A higher share of incorrect behaviours can be seen in the case of heavy vehicles, which are influenced by the available swept path (Fig. 7).

The incorrect driver behaviours are caused by the desire to pass through the roundabout at higher speeds; when the drivers select the faster path, which happens in the absence of lane dividers. The comparison of speed when passing in a correct and incorrect way indicates that the absence of lane dividers is associated with an increase in speed, especially at the entry and exit of the roundabout (Figs. 8 and 9). Approaching speed for incorrectly driving is greater because drivers, who are familiar with traffic organization of turbo-roundabout, are able to change trajectory on roundabout because of lack of lane dividers.

Lane dividers force drivers to correct passage in accordance to the designed corridor, what leads to speed reduction, particularly at the approach and entry to the roundabout (Fig. 9).

In the absence of adequate data on accidents and high uncertainty about data regarding collisions, the decision was made to perform a relative assessment of road safety in relation to the traffic lanes in the roundabouts, as well as to roundabouts with and without lane dividers. The values of the average speed of vehicles in free flow when passing through the roundabout (from the sections at the entry, exit and the roadway) was used as a surrogate road safety measure for turbo-roundabouts.

The value of speed [km/h] necessary to estimate changes in road safety (based on models (3)–(5)) can be obtained based on empirical measurements or speed models. For the purpose of this second approach, average speed estimation models were developed based on the observed speed for the entry, exit and circulatory roadway of the roundabout, depending on the radius of curvature for entry R_{en}, circulatory roadway R_{cir}, exit R_{ex} and the speed of approaching the roundabout S_{app}:

Entry speed: $S_{en} = 5.54 + 0.485 \cdot S_{app} + 0.432 \cdot R_{en}$, $R^2 = 0.74$
($R_{min} = 12\,\text{m}$, $R_{max} = 32\,\text{m}$) (6)

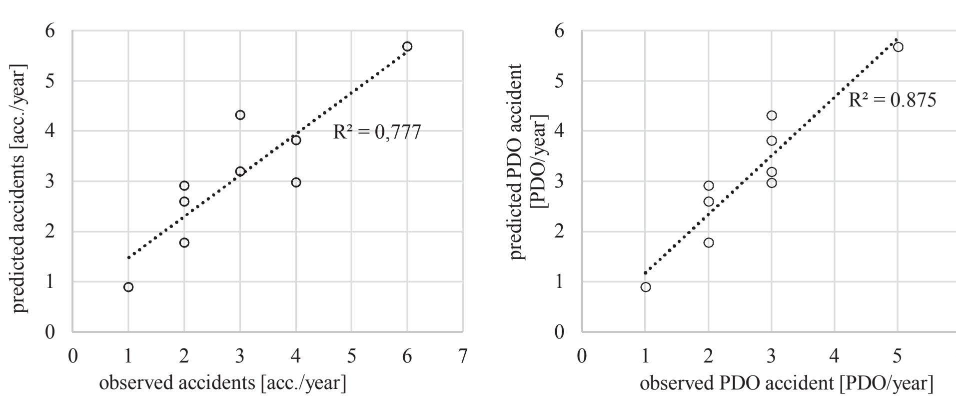

Fig. 5. Relationship between observed and predicted values for accidents and PDO accidents.

Table 4
The List of the Observed Speed Parameters for the Analysed Turbo-Roundabouts.

Speed parameters [km/h]	inner lane, section				outer lane, section			
	approach	entry	circulatory	exit	approach	entry	circulatory	exit
S_A	53.1	34.1	29.8	34.6	50.1	34.2	31.6	34.4
S_{15}	38.7	22.9	23.1	28.4	38.1	24.9	25.4	28.1
S_{85}	67.5	46.1	37.3	41.3	61.8	43.1	38.0	41.3
Stddev	13.9	10.5	6.8	6.2	11.6	8.5	6.5	6.8

Circulatory speed: $S_{cir} = 22.2 + 0.358 \cdot R_{cir}$, $R^2 = 0.36$ ($R_{min} = 11$ m, $R_{max} = 34$ m) (7)

Exit speed: $S_{ex} = 27.28 + 0.384 \cdot R_{ex}$, $R^2 = 0.24$ ($R_{min} = 12$ m, $R_{max} = 30$ m) (8)

The values in brackets indicate ranges of variability of radii. Based on the estimated values of speed and observed average speed of passing through the roundabout, average speed *AS* was established for turbo-roundabouts with and without lane dividers.

As the observation shows, the average speed of passing through the roundabout with lane dividers AS_d changed from 25 km/h to 42 km/h. A linear regression model of estimation AS_d developed using the method of ordinary least squares (OLS) and the value from models (6)–(8) for correct driving (drivers staying in lane) is presented below:

$$AS_d = -6.87 + 0.334 \cdot S_{en} + 0.394 \cdot S_{cir} + 0.482 \cdot S_{ex}, \text{ [km/h]} R^2 = 0.98 \quad (9)$$

An estimation model for the average speed of vehicles passing through the roundabout without lane dividers AS_{nd} was developed with assumption average difference between turbo-roundabouts with and without dividers for correct driving (calculated based on Eqs. (6)–(8)) and various percent of incorrect driving. The percentage of incorrect passages, which affects the increase in vehicle speeds, was introduced into the model as one of the independent variables:

$$AS_{nd} = AS_d + 1.41 + 0.123 \cdot P_{incdrv}, \text{[km/h]} R^2 = 0.81 \quad (10)$$

where:

P_{incdrv} = percent of incorrect driving [%] (range 15%–40%)

Higher speed at turbo roundabout without dividers (average 1.41 km/h) is caused by drivers who drive faster by changing trajectory but staying in lane. It means that drivers drive faster without a physical limitation of the traffic corridor. It is especially noticed at entry to the turbo-roundabout.

For developed speed models, a simulation of speed percentage change in the number of accidents for turbo-roundabouts with and without lane dividers was carried out, according to the Eqs. (3)–(5) in regard to traffic in the outer lane of the roundabout.

The results demonstrate a negative impact of the absence of lane dividers on road safety (Fig. 10). Their absence results in a significant increase in the number of accidents. The applied SPFs do not offer conclusive results as to the value of the change, but the proportions in relation to roundabouts with and without lane dividers and to roundabout lanes are similar. Unfortunately, the presented analyses do not allow to estimate the changes in the number of accidents.

The AS_{nd} speed model allowed to estimate the impact of drivers' incorrect behaviour on a potential change in the number of accidents at roundabouts without lane dividers (Fig. 11). Therefore, it has become

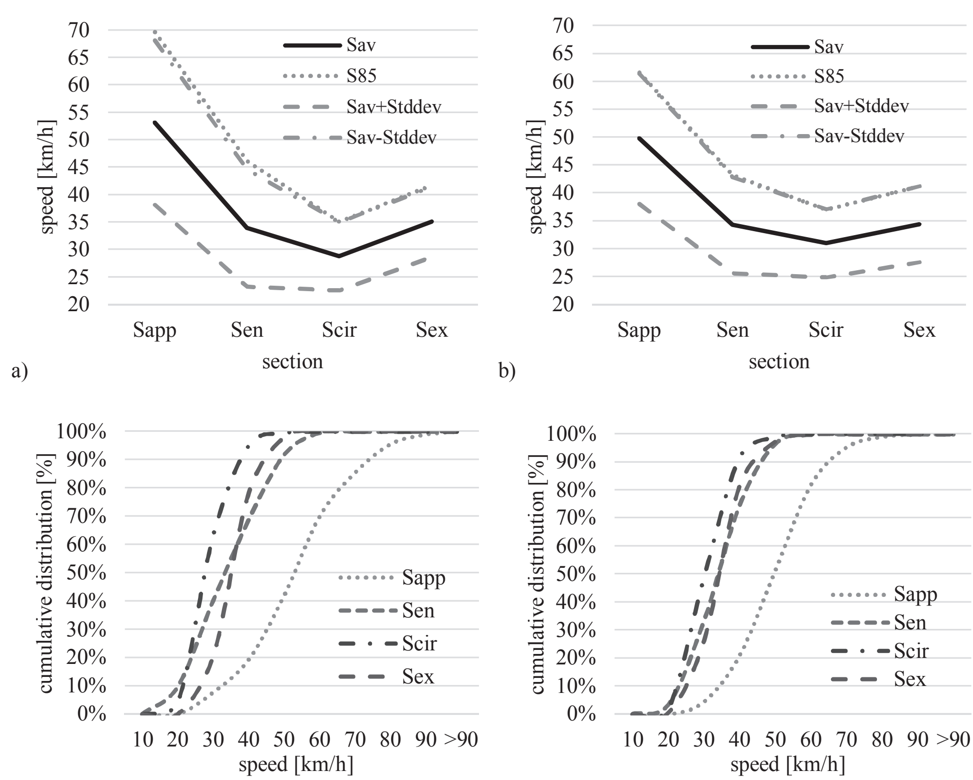

Fig. 6. Speed profile on the section of passing through the roundabout and speed distribution function for the inner lane (a) and the outer lane (b).

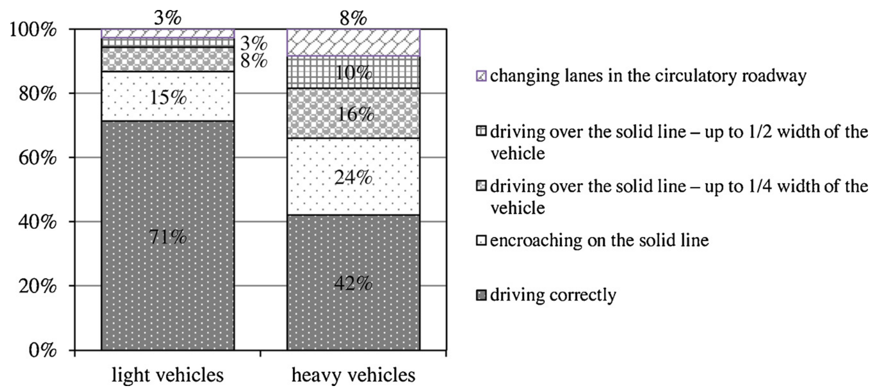

Fig. 7. Comparison of behaviours in turbo-roundabouts for light and heavy vehicles.

clear that the increase in incorrect passages may lead to an increase in the number of accidents.

Also in this case, due to significant divergences in the predicted number of accidents from the calculations made according to applied models, it is difficult to indicate a quantitative influence of incorrect passages on the number of accidents. For US model the impact of speed on road safety is the highest and for IT model the lowest.

5. Discussion

Speed profile analysis for drivers passing turbo-roundabout indicated that the approaching speed to the turbo-roundabout is a significant factor in average speed. In order to improve road safety, further research should focus on geometrical parameters on approach and entry and their impact on the speed of vehicles at the turbo-roundabouts.

The similar results for developed SPF, with lane dividers as a binary variable, and US model may be due to the specific nature of geometric design of roundabouts in the United States, which often leads to higher travel speed similar to those observed at turbo-roundabouts without lane dividers (TRB, 2010).

The presence of lane lane dividers is associated with decrease in the average speed by 1.4 km/h on average for drivers staying in lane. In the case when the average speed is about 30–40 km/h, it is equal to approx. 4% difference. The additional impact of lane violations on average speed is greater, it is equal to approx. 15% difference. The number of incorrect behaviors probably can be an auxiliary factor for determining the speed as a surrogate safety measure.

The impact of improperly driving vehicles on the speed is low, however, considering that the increase in speed mainly concerns the area of crossing traffic flows, its likely statistically significant impact on the accidents and PDO accidents seems to be justified.

The disadvantage of the developed surrogate safety measure is the lack of linking the frequency of the violation of the adjacent lane with the traffic volume. One of reasons may be that speed analysis was

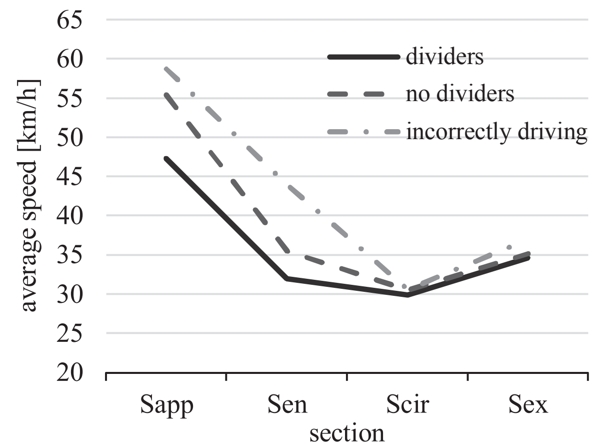

Fig. 9. Speed profile at the turbo roundabouts with and without lane dividers and incorrect driving.

conducted for free flow, while accident frequency may be related not only to free-flow conditions. This may limit the statistical significance of speed effect in SPF. Another limitation was the small sample of injury accidents (in total only 6 injury accidents of 9 analyzed turbo-roundabouts), which was not sufficient for developing a SPF.

Turbo-roundabout geometry is much more complex (various radii around central island) and difficult to describe in relation to single-lane roundabouts, where geometrical parameters (radii) are fixed. Therefore aapplication of speed assessment method with GPS data can limit the problems arising in study from the geometrical design of turbo-roundabouts and give possibilities to appropriate assess variability of travel path and its relationship with geometry.

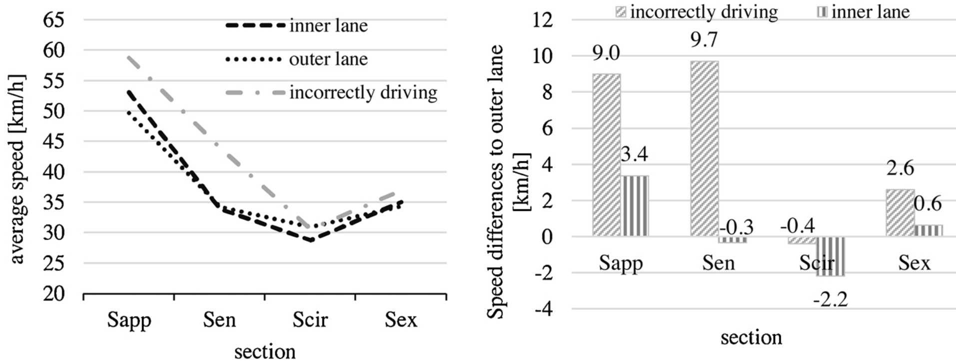

Fig. 8. Speed profile on the section of passing through the roundabout for correct and incorrect driving.

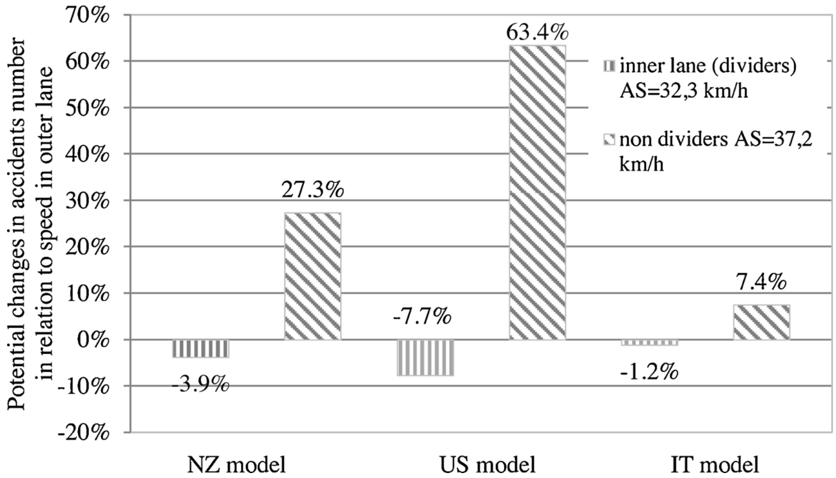

Fig. 10. The potential change in the number of accidents at turbo-roundabouts depending on the observed values of average speed.

6. Conclusions

Increasingly popular turbo-roundabouts enable improving traffic performance while maintaining a high level of road safety. However, in the absence of sufficient data, especially in the case of specific solutions such as non-standard geometrical parameters, the actual assessment of the safety performance is problematic. For this reason, drivers' behavioural studies have been undertaken as a surrogate safety measure in turbo-roundabouts in Poland.

Due to the lack of reliable data on accidents it is not possible to assess and validate any relation between direct and surrogate measures. Therefore, the presented results allow to present safety performance function with binary variable of presence of lane dividers. This allows only a relative assessment of scenarios with and without lane dividers or different geometrical parameters (radii of trajectory).

Based on the conducted research, the following conclusions have been drawn:

- The studies have clearly confirmed that the presence of lane dividers has a direct influence on the decrease in the speed with which drivers pass through the turbo-roundabout. The application of physical raised elements creates swept paths, which dictate driving trajectory selection.
- The results obtained indicate that the geometric design is a crucial factor determining the choice of speed when passing through the roundabout.
- The measurements taken only confirmed the efficiency of raised lane dividers. In practice, their application rules out incorrect drivers' behaviours while not impeding the changing of lanes.
- The presented SPF allows the assessment of presence of lane dividers on number of injury accidents and PDO accidents and also of a relative change in road safety based on the changes of the observed or estimated speed.
- The use of the average speed for passing the roundabout as a surrogate safety measure allows the estimation of road safety in turbo-roundabouts with and without lane dividers and different geometrical parameters (radii of trajectory).
- It is necessary to develop and validate SPFs, which will require a reliable and qualitative database.
- It is possible to use the above-mentioned approach to assess road safety on other intersections with a circulatory roadway.
- The application of the FCD technology to collect data improved the quality of models through the assessment of precise values of the radius of trajectory and speed, This approach is promising – in the further research, data from GPS devices may be used for calibration of SPF and assessment of road safety on turbo-roundabouts based on big data (FCD from vehicle fleets).

The presented results can be used in a pro-active assessment of turbo-roundabouts with and without lane dividers in various countries. As opposed to “waiting for accidents to happen”, the proposed approach will allow preventive evaluation at the phase of the design or

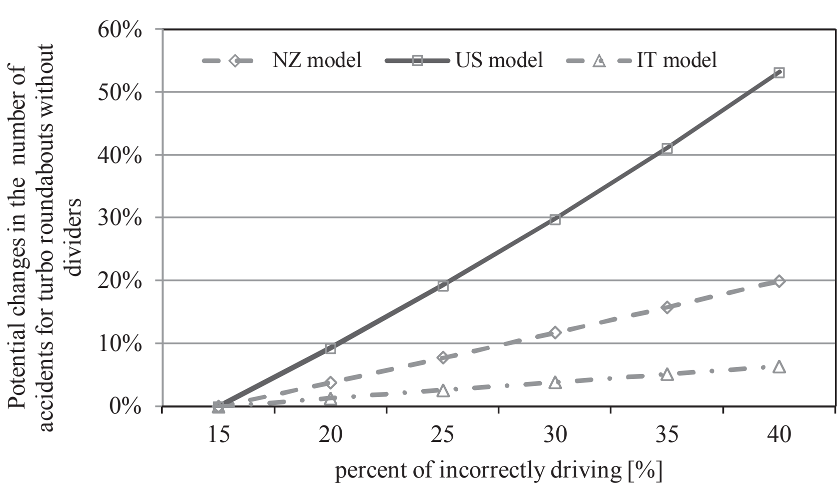

Fig. 11. The influence of incorrect passages on the change in the number of accidents for turbo-roundabouts.

shortly after the construction of roundabouts.

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