Safety Evaluation of Turbo-Roundabouts Using Floating Car Data and Video Observation

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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 is to develop 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 will be to use the 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 is based on speed and lane behaviour. Speed was obtained from video observations and floating car data, which enable the construction of representative speed profiles. Lane behaviour data were 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 will also enhance the existing accident prediction models, combining traffic volumes, trajectory geometry and speeds. The final models can help quantify the safety impact of different turbo-roundabout solutions.

Keywords

turbo-roundabout, surrogate safety, speed, floating car data

1. Introduction

Intersections are crucial elements which influence the security and efficiency of traffic in the road network. 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 intersections are single-lane roundabouts. Despite the numerous benefits of this type of intersections, their application is not always justified or possible, eg.: in cases of intersection of multi-lane roads or the reduction in intersection capacity (in favourable conditions estimated to be around 2,500 veh/h). Multi-lane roundabouts boast a greater capacity, however they significantly outnumber single-lane roundabouts in terms of the number of registered accidents and collisions. The geometric layout of such an intersection results in higher speed, more frequent manoeuvres of changing lanes within the roadway of the roundabout as well as the 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 of the environment has led to the application of different circular intersection solutions.

The solution which was arrived at while trying to find a compromise between safety and higher capacity is: turbo-roundabouts, which were first applied in the Netherlands. Turbo-roundabouts are the solution which, being an alternative to multi-lane roundabouts, help to simplify the process of drivers' decision making, limit lane changing and reduce collision points in the roundabout as well as induce low driving speed due to raised lane dividers. As a result, turbo-roundabouts are generally well-received and applied more and more often around the world.

Also in Poland turbo-roundabouts are beginning to be used more and more often, even though there are no uniform (mandatory) 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 one from another, while displaying a number of characteristic features typical of the Dutch solutions. One of the features which differentiates such intersections, not only in Poland but also in other countries, is the method of separating the traffic lanes in the circulatory roadway and/or entries into the roundabout, which can have a considerable influence on road safety, winter maintenance as well as drivers' behaviour.

Foreign experiences prove that turbo-roundabouts are a safe solution. However, it is difficult to estimate the potential for reducing accidents by building turbo-roundabouts in comparison to other types of intersections. As the research results show, the safety impact of turbo-roundabouts has not been sufficiently studied. This results from the fact that there is a small number of turbo-roundabouts, the time for the analysis of the before-after effect has not been sufficiently long, accidents have been rare and there is incomplete data on registered collisions (property damage only).

Previous studies [1], [2], [3] applied only naive before-after designs or relied on traffic conflicts in micro-simulations [4], [5], [6]. The results of the "before and after" analysis carried out in the Netherlands [1] indicate that the potential for reducing accidents is close to that of single-lane roundabouts, with ca. 75%.

Using a developed model for the potential accident rate evaluation, Mauro and Cattani [7] 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% than in the case of multi-lane roundabouts. The authors emphasise that the results were obtained on the basis of an extension of the theoretical model of multi-lane roundabouts onto turbo-roundabouts, but without calibration, so the calculations may be prone to errors.

One of the factors that can have a positive impact on traffic safety at turbo-roundabouts are raised lane dividers [1], [8]. Their application varies from country to country, e.g. in Germany [9] they are not accepted due to the concern about motorcyclists' safety, implementation costs and problems with winter maintenance. Moreover, drivers' abnormal behaviour does not pose such a significant hazard that the advantages of the solution would outweigh the risk it carries. 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 [10].

The aim of the performed analysis was to compare the functioning of roundabouts with a physical separation of lanes with no raised lane dividers. One of the conclusions indicated that the level of traffic safety at turbo-roundabouts without a physical separation between lanes is similar to that of multi-lane roundabouts, whereas the application of raised lane dividers increases the level of safety. This assessment has been carried out on the basis of a small number of roundabouts with and without dividers.

Limited and often not sufficiently precise accident data, both in terms of accidents and collisions, as well as difficulties in obtaining necessary data to conduct comparisons of the relative safety risk regarding the traffic on different intersections (e.g. traffic volume, directional structure), indicate the need for safety assessment using a surrogate safety measurement. Such assessment measures include incorrect behaviours of drivers as well as the speed of vehicles.

The studies consider speed as a factor influencing the level of traffic safety on intersections with a circular roadway. This is indicated by the studies carried out with the use of accident prediction models where among independent variables the average speed of vehicles in the roundabout roadway is considered statistically significant [11], [12], [13].

The results of the studies suggest that the available theoretical speed of vehicles in the roundabout is strictly connected with its type and geometry (Figure 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 [1]. 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.

![Figure 1: The impact of the type of a circular intersection on the vehicle speed [1].](image-url)
Following the previous Polish studies [10], [14], [15], the primary objective of the paper is to develop a reliable and valid surrogate safety measure based on the field data, which will overcome 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.

The surrogate safety measure consists in road users' interactions, which means speed and lane behaviour. Speed and lane behaviour are obtained from video recording and floating car data, which will enable the construction of representative speed profiles.

2. Methodology

The research on road safety in turbo roundabouts assumed that a surrogate road safety measure will be: vehicle speed and drivers' behaviour.

The main objective of the speed research carried out on the analysed roundabouts was to indicate that there is a relation between the geometry of intersections and the speed of a vehicle passing through a turbo-roundabout. For this reason, video monitoring was conducted (of speed in cross-sections and drivers' behaviours), as well as the results of floating car data for selected polygons were analysed. Studies using the GPS technology were carried out to help build speed profiles for passing a turbo-roundabout and the trajectory of this passing. Tests using GPS allow to limit the problems arising in research from the geometry of turbo-roundabouts. The design of this type of intersections results in the fact that it is difficult to clearly designate curvatures in comparison with single-lane roundabouts. Based on the above-mentioned methods, drivers' behaviours were assessed both in roundabouts with and without dividers.

The traffic analysis using video recording was carried out at turbo-roundabouts located on roads situated in a built-up area with the speed limit of 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. Figure 2 shows examples of research sites without dividers (a) and with dividers (b). Each measurement lasted approximately 5 hours.

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. Data were collected in free flow speed conditions basing on driving in car, which was equipped in GPS device, behind observed vehicle in constant gap between vehicles. In total, results were obtained for 100 tracks of vehicles passing the roundabout.

![Figure 2: Examples of research sites without dividers (a) and with dividers (b).](image-url)
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 (Figure 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 turbo-roundabouts was specified based on these designs.

Figure 3: The examples of data collection set and measurement speed sections: 1 – approach \(S_{\text{app}}\), 2 – entry \(S_{\text{en}}\), 3 – circulatory roadway \(S_{\text{cir}}\), 4 – exit \(S_{\text{ex}}\).

The studies in FCD technology have been carried out using a VIDEO VBOX recorder (Figure 4) which is a 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 frequency 0.1 sec. The precision of this procedure was sufficient to render the detailed trajectory of the analysed vehicle. A test vehicle followed the analysed vehicle at a constant distance, registering indirectly its trajectory and speed. This made it possible to register a driver’s random behaviour on roundabouts.

Figure 4: VIDEO VBOX set used in the speed test [16].

The data about the position of the vehicle in motion was used to recreate its trajectory in AutoCad civil 3D (Figure 5). Based on this, the actual values of the radii of curves were determined and values of the registered speed were attributed to them, thus creating speed profiles.
Based on video recording and floating car data speed prediction models were developed for: entry, circulatory and exit sections separately and for passing through roundabout. Model predicting average speed $AS$ through roundabout was developed using the most popular OLS regression approach. Predicted value of $AS$ was used as a surrogate safety measure to calculate relatively impact of dividers presence on road safety. To this end, authors applied the existing prediction models for roundabouts, which take into account speed as an independent variable.

a) NZ (New Zealand) model [11]

\[ Acc = 6.12 \times 10^{-8} \cdot Q_e^{0.47} \cdot Q_c^{0.26} \cdot S_C^{2.13} \]  

(1)

b) US model [13]

\[ SPF = \beta_0 \cdot AADT^{0.5094} \cdot ASS_{predicted}^{4.3314}, \ln \beta_0 = -16.3755 \]  

(2)

c) IT (Italian) model [13]

\[ SPF = \beta_0 \cdot AADT^{2.8623} \cdot ASS_{predicted}^{0.6339}, \ln \beta_0 = -29.5239 \]  

(3)

where:
- $Acc =$ annual number of crashes,
- $Q_e =$ entering flow on the approach,
- $Q_c =$ circulating flow,
- $S_C =$ free average speed of circulating vehicles as they pass the approach being modelled,
- $SPF =$ Safety Performance Function,
- $AADT =$ Annual Average Daily Traffic,
- $ASS_{predicted} =$ approach average predicted speed.

As a second surrogate safety measure incorrect behaviours based on the video recording on turbo-roundabouts were identified, among others:
- driving over the edge of the lane (separately for inner and outer lanes, cutting the curves),
- needlessly changing traffic lanes which is not a result of wrong lane selection at entry (changing lanes is not caused by the inability to continue driving in the chosen direction in a given lane).

3. Analysis and Results

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 1, Figure 3) for the following sections of the roundabout (described in point 2).

The results presented in Table 1 concern correct passages through the turbo-roundabout both in the case of the presence of dividers and their absence. Incorrect passages were rejected 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.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>inner lane, section</th>
<th>outer lane, section</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>approach entry</td>
<td>circulatory exit</td>
</tr>
<tr>
<td>$S_a$ [km/h]</td>
<td>53.1</td>
<td>34.1</td>
</tr>
<tr>
<td>$S_{15}$ (km/h)</td>
<td>38.7</td>
<td>22.9</td>
</tr>
<tr>
<td>$S_{85}$ [km/h]</td>
<td>67.5</td>
<td>46.1</td>
</tr>
<tr>
<td>Stddev [km/h]</td>
<td>13.9</td>
<td>10.5</td>
</tr>
</tbody>
</table>

The comparison of the vehicles’ speed at the lanes indicate higher speeds at the approach to the turbo-roundabout on 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. 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 a circulatory roadway 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 1) and cumulative speed distribution functions (Figure 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 has greater influence than the geometrical solution.

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

![Figure 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).](image-url)
The next step of the empirical research involved comparing the behaviour of drivers passing through the roundabout without dividers correctly and incorrectly. The incorrect behaviours make up circa 1/3 of all the passages observed. A higher share of incorrect behaviours can be seen in the case of heavy vehicles, which has to do with the swept path (Figure 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 when there are no dividers. The comparison of speed when passing in a correct and incorrect way allows the conclusion that the absence of dividers causes an increase in speed, especially at the entry and exit of the roundabout (Figure 8).

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 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 necessary to estimate changes in road safety (based on models (1), (2), (3)) 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:**

$$S_{en} = 5.54 + 0.485 \cdot S_{app} + 0.432 \cdot R_{en} \ , \quad R^2 = 0.74 \quad (R_{min} = 12 \text{m}, \ R_{max} = 32 \text{m}) \quad (4)$$
Circulatory speed:

$$S_{cir} = 22,2 + 0,358 \cdot R_{cir}, \quad R^2 = 0,36 \quad (R_{min} = 11m, \ R_{max} = 34m)$$ (5)

Exit speed:

$$S_{ex} = 27,28 + 0,384 \cdot R_{ex}, \quad R^2 = 0,24 \quad (R_{min} = 12m, \ R_{max} = 30m)$$ (6)

In the brackets are indicated ranges of variability of radii. The low value of $R^2$ for $S_{cir}$ and $S_{ex}$ is caused by high variability of speed at relatively low values of curves radii and it is related to choice swept path by drivers. However, based on literature review for operating speed on curves [17] similar values of $R^2$ are observed.

Based on the estimated values of speed and observed average speed of passing through the roundabout, $AS$ was established for turbo-roundabouts with and without dividers.

As the observation shows, the average speed of passing through the roundabout with 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 (4), (5), (6) are presented below:

$$AS_d = 6,87 + 0,334 \cdot S_{en} + 0,394 \cdot S_{cir} + 0,482 \cdot S_{ex}, \quad R^2 = 0,98$$ (7)

An estimation model for the average speed of vehicles passing through the roundabout without dividers $AS_{nd}$ was developed with OLS approach too. The percentage of incorrect passages, which affect the increase in vehicle speeds, was introduced into the model as one of the independent variables:

$$AS_{nd} = AS_{d} + 3,66 + 0,021 \cdot P_{incdrv}, \quad R^2 = 0,81$$ (8)

where:

$P_{incdrv}$ – percent of incorrect driving [%] ($P_{incdrv \min} = 15\%, \ P_{incdrv \max} = 40\%$)

For developed speed models, a simulation of speed percentage change in the number of accidents for turbo-roundabouts with and without dividers was carried out, according to the equations (1), (2) and (3) in regard to traffic in the outer lane of the roundabout.

The results demonstrate a negative impact of the absence of dividers on road safety (Figure 9). Their absence results in a significant increase in the number of accidents. The applied safety models do not give conclusive results as to the value of the change, but the proportions between them in relation to roundabouts with and without dividers and to roundabout lanes are similar. Unfortunately, the presented analyses do not allow to estimate the value of change in the number of accidents.

![Figure 9: The potential change in the number of accidents at turbo-roundabouts depending on the observed values of average speed.](image)

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 dividers (Figure 10). Therefore, it has become 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.

Figure 10: The influence of incorrect passages on the change in the number of accidents for turbo-roundabouts.

4. Conclusions

Increasingly popular turbo-roundabouts allow for designing capable of 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 dividers, 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 and collisions it is not possible to assess and validate any relation between direct and surrogate measures. Therefore, the presented results only allow to conduct a relative assessment of the changes in the traffic safety in turbo-roundabouts with and without dividers. Based on the conducted research, the following conclusions have been drawn:

• The studies have clearly confirmed that the presence of dividers has a direct influence on the decrease in the speed with which drivers pass through the turbo-roundabout. The application of elements which are raised above the upper surface of the roadway results in swept patch which drivers are compelled to use.

• 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 dividers. In practice, their application rules out incorrect drivers' behaviours while not impeding the changing of lanes. Lanes can be changed at any time on sections with no dividers which ensure the route's passability.

• The presented method allows the assessment 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 as a surrogate safety measure allows the estimation of road safety in turbo-roundabouts with and without dividers.

• The comparison of the existing safety models, which take into account speed as an independent variable, indicated a significant difference in the value of estimated number of road incidents, which may result from local conditions for which these models had been designed.

• It is necessary to develop and validate safety models, which requires a reliable and qualitative data base.

• 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.
The presented results can be used in a pro-active evaluation of turbo-roundabouts with and without 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 shortly after the construction of roundabouts.

References

16. www.vboxmotorsport.co.uk