

THE ROAD SAFETY AT TURBO ROUNDABOUTS IN POLAND

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Abstract: *There are two groups of turbo roundabouts used currently in Poland. The first group is turbo roundabouts with geometry and traffic organization designed following the model of Dutch turbo roundabouts with raised lane dividers. The other group is turbo roundabouts with traffic organization which entirely or partly corresponds to traffic organization of conventional turbo roundabouts, but with lane dividers not present, with their function performed by a single continuous line of P-2 type. Turbo roundabouts in the world are considered as solutions which are characterized by a high level of road safety and allow for effective flow at substantial traffic intensities. The data about turbo roundabouts in Poland analysed by the author show that there are substantially more turbo roundabouts without raised lane dividers. The paper attempts to answer to the question of whether turbo roundabouts with lane dividers in the form of a single continuous line ensure the appropriate level of road safety. Furthermore, the comparison of the level of road safety in turbo roundabouts equipped in raised lane dividers with turbo roundabouts with lane separators in the form of continuous line revealed that turbo roundabouts with raised lane dividers are safer solutions than turbo roundabouts with traffic lane dividers in the form of continuous line.*

Key words: *turbo roundabouts, road safety, traffic engineering.*

1. Introduction

Numerous studies (including: Swov Fact Sheet, 2012; Krystek, Jamroz, Michalski et al; Legac, Pilko and Brčić, 2012; Legac, Pilko and Šubić, 2012; Macioszek, 2013b; Małecki, 2012; Małecki and Wątróbski, 2010; Šubić, Pilko and Legac, 2012; Šubić, Pilko and Tepeš, 2012; Stone, Chae and Pillalamarri, 2002; Szczuraszek, 2005; Szczuraszek and Macioszek, 2013) have demonstrated that single-lane roundabouts ensure the level of road safety higher than other types of intersections. This fact caused that, since nearly twenty years, they have been very popular among designers and used in both build-up and outside areas. High level of road safety in single-lane roundabouts can be ensured in particular due to:

- low times of passing through the intersection, ranging from 20 to 30 km/h, which has been demonstrated in previous studies (Macioszek, 2011a; Macioszek, 2012a; Macioszek, Sierpiński and Czapkowski, 2010a; Macioszek, Sierpiński and Czapkowski, 2010b; Macioszek, 2012c),
- lower number of collision points compared to other types of intersections,
- separation of traffic flow at the entries from the flow at the exits through splitter islands, which

causes that pedestrians are able to cross the entry and exit separately,

- lower time loss compared to other types of intersection, which attracts lower fuel consumption, lower environmental pollution and lower costs of driving through the crossing (Al-Madani, 2003; Tollazzi, Rencelj, and Turnsek, 2011; Várhelyi, 2002).

One of the main limitations in using small single-lane roundabouts (despite the fact that they are the safest types of roundabouts) is their traffic capacity, which is estimated at 2,000 to 2,500 vehicles per hour (Brilon, Stuwe, and Bondzio, 1993; Macioszek, 2011b; Mauro, 2010). Due to this fact, two-lane roundabouts started to be built in the intersections where streams of high traffic intensity cross with each other. Furthermore, in large two-lane roundabouts, big distances between the entries cause that the vehicles move at higher speeds than it is the case on single-lane roundabouts. The traffic flow of the vehicles leaving the roundabout interweaving with the flow on the external lane. These situations generates additional traffic collision points and leads to the deterioration of traffic conditions and consequently to a general decline in the level of road safety. The practice shows that two-lane roundabouts with external diameter reduced to even 50 m cause a decline in traffic capacity (as drivers

are unwilling to use the internal lane because the small external diameter does not allow them to see the surroundings through mirrors and they are afraid that they would not leave the circular roadway through the desired exit due to a high traffic volume of the vehicles moving on the external traffic lane), increased speed of the vehicles on the circular roadway and higher number of road traffic collision points.

In the Netherlands in 1996, L. Fortuijn designed a new type of multi-lane roundabouts, termed turbo roundabouts, which have a number of advantages compared to conventional multi-lane roundabouts. Turbo roundabouts are capable of reaching higher traffic capacity compared to conventional two-lane roundabouts while ensuring the level of road safety similar to single-lane roundabouts. With the course of time and based on positive experience of the Dutch solutions, other countries, including Poland, started to build these intersections due to improved road safety conditions and enhanced traffic capacity. There are a number of reasons, both technical (e.g. problems of effective run off water from the roundabout, problems of winter maintenance and the number of long heavy vehicles in the traffic) and social (e.g. problem of social acceptance of new road traffic solutions) which caused that raised lane dividers have not been built in many turbo roundabouts present in Poland. This fact caused that in Poland today, there are both roundabouts which are designed in terms of geometry and traffic organization following the model of Dutch turbo roundabouts i.e. with raised lane dividers, and turbo roundabouts with traffic organization that corresponds entirely or partially to traffic organization typical of turbo roundabouts without raised lane dividers while their function is replaced by a single continuous line of P-2 type. Based on the inventory of the Poland's area and turbo roundabouts identified by the author, one can note that currently there are considerably more turbo roundabouts without raised lane dividers.

According to (Bulla and Castro, 2011; Fortuijn, 2007; Giuffrè, Guerrieri and Grana, 2009; Macioszek, 2013a) turbo roundabouts are considered in the world as solutions that allow for efficient flow at considerable road traffic intensities. Based on the data concerning traffic events obtained from SEWiK (the Road Accident and Collision Register in Poland), the paper attempts to investigate

whether the turbo roundabouts in Poland with traffic lane dividers in the form of the P-2 continuous line ensure an appropriate level of road safety. The next part of the paper compares the structure of traffic events that took place in turbo roundabouts equipped and not equipped in raised lane dividers.

2. Characteristics of turbo roundabouts

Turbo roundabout is a multi-lane roundabout with spiral markings and separated lanes for particular directions. Turbo roundabouts (similar to spiral ones) are characterized by preference for a selected direction of traffic (only usual roundabouts treat all the road users similarly at any entry). Road users at the entries to turbo roundabouts are forced to choose a demanded direction of driving. The choice or changes in the direction while driving through the roundabout is impossible as the vehicle streams from the internal and external lanes do not intersect. Depending on the number of traffic lanes at the entries and exits, it is possible to configure the roundabout so that returning on one of the directions is impossible. Fig. 1 illustrate the example diagrams of turbo roundabouts.

The main characteristics of turbo roundabouts include (Fortuijn, 2003):

- presence of more than one traffic lanes on the roundabout,
- the choice of a driving direction is possible only at the entry (the change is impossible at the circular roadway due to the lane dividers which separate individual lanes on the circular roadway and the entries),
- presence of not more than two traffic lanes on the circular roadway in the area of entries, where the vehicles from the entries have to give way to other vehicles,
- lack of option of intersecting vehicle streams in the areas of roundabout roadway through the use of spiral horizontal marking connected with spiral shape of the roundabout's roadway (Fig. 1),
- in some cases lack of option of returning on one of the traffic directions.
- Turbo roundabouts have the following advantages (Corriere and Guerrieri, 2012; Engelsman and Uken, 2007; Giuffrè, Guerrieri and Grana, 2009; Yperman and Immers, 2003),

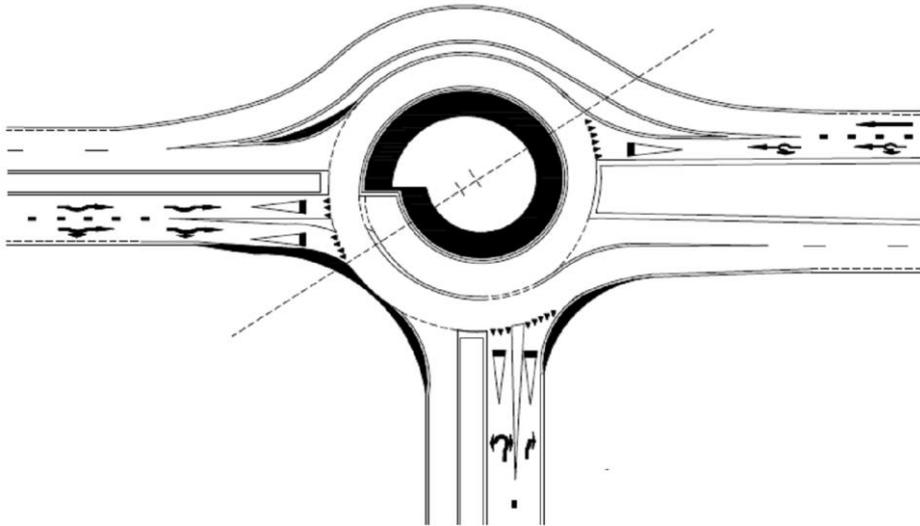


Fig. 1. Three entries turbo roundabout scheme (Fortuijn, 2003)

- giving way by the drivers from entries to maximum two traffic streams moving on the divided traffic lanes,
- reduction in the number of collision points,
- relatively low speed of the vehicles on the roundabout (similar to the speed of vehicles on a single-lane roundabout) caused by both specific geometry of the intersection and the raised lane dividers,

opportunities for reaching higher traffic volumes compared to the traffic volumes of the two-lane roundabouts.

3. The state of road safety on turbo roundabouts – a study of literature

Intersections with circular traffic are characterized by lower number of collision points compared to the intersections without traffic signals with similar configuration of entries and road lanes where the traffic is controlled by traffic signs: A-7 and/or B-20.

The four-legs turbo roundabouts have no collision points at leaving the circulatory roadway while the total number of collision points depends on number of lanes in area of roundabout. For comparison, there are 8 collision points in four-legs single-lane roundabouts with single-lane entries and exits. Furthermore, there are 22 collision points in four-legs two-lane roundabouts with two-lane entries and

exits. According to Corriere and Guerrieri (2012) compared to two-lane roundabouts, turbo roundabouts are characterized by nearly 60% reduction in the number of potential collision points.

Based on the overview of world literature, one can emphasize that a relatively small number of collision points in turbo roundabouts translates into a high level of road safety. The information presented in the literature shows that turbo roundabouts are numbered among the safest solutions for road intersections which are safer than the multi-lane roundabouts. The conclusions from the studies that have evaluated road safety in turbo roundabouts are compared in Table 1.

4. The state of road safety on turbo roundabouts in Poland with traffic lane separators as a single continuous line P-2 type

It was frequently found during the inventory made in the area of Poland that the solutions which in fact do not have many common features with actual turbo roundabouts are often taken for turbo roundabouts. After initial selection of the roundabouts, the analysis focused on 10 turbo roundabouts with traffic lane dividers in the form of a single continuous line of P-2 type. All the locations selected for the analysis are the intersections that represent critical points in the road and street

network where considerable levels of traffic volumes are reported. These included, among others, the roundabouts in Zabrze (two roundabouts), Sosnowiec, Prądy near Opole, Szczecin, Bielsko-Biała (two roundabouts), Sieradz and Radom (two roundabouts).

The period of the analysis was the years 2010-2012. The data for analysis were obtained from the "System Ewidencji Wypadków i Kolizji" (SEWiK - the Road Accident and Collision Register in Poland) from several police headquarters. At the initial stage, the analysis were carried out for each location separately. The paper presents the further stage of

the analyses that includes combined comparisons for all the analysed objects. This form of data presentation was aimed at obtaining information about the most frequent types of traffic events that occur in turbo roundabouts with traffic lane dividers in the form of a single continuous line and causes of these events.

In general, it can be concluded that the results obtained for the distribution, location, frequency and type of traffic events are consistent with the results of the international and national survey with respect to the traffic events in multi-lane roundabouts (Kimber, 1980; Macioszek, 2012b).

Table 1. The conclusions from international scientific researches on road safety on turbo roundabouts

Country	Autor (-s)	Conclusions
Holland	Fortuijn (2007, 2009)	The risk of injury following a road traffic accident or collision on turbo roundabouts is by 80% lower than in other types of multi-lane roundabouts. In a longer period, a slightly lower reduction (by 70%) is expected compared to the conditions in single-lane roundabouts.
	Wijk (2009)	Turbo roundabouts are by 70% safer than intersections without traffic lights, by 50% safer than intersections with road traffic lights and from 20 to 40% less safe than single-lane roundabouts.
Italy	Mauro and Cattani (2010)	A degree of improvement in road safety on the turbo roundabouts depends on the traffic organization, intensity and directional structure of traffic and ranges from 40 to 50% for road traffic accidents and 20 to 30% for road traffic collisions.
	Giuffrè, Guerrieri and Grana (2010)	After reconstruction of three intersections into turbo roundabouts, road safety conditions improved while driving speed considerably reduced.
Slovenia	Brilon (2008)	No traffic events with serious consequences were recorded (analysis was carried out in one location).
Slovakia	Tollazzi, Rencelj and Turnsek (2011)	Turbo roundabouts are the solutions which are characterized by a very high level of road safety.
Colombia	Bulla and Castro (2011)	Turbo roundabouts exhibit improvement in the level of road safety by 22%.
Poland	(Web page)	After reconstruction of the roundabout into a turbo roundabout (with lane dividers in the form of a single continuous line) the number of collisions declined by ca. 80%.
	Macioszek (2013c, 2013d)	The conclusions concerning turbo roundabouts with raised lane dividers are: In general, high level of road safety can be recorded in these intersections. No fatalities were reported during the period of the analysis. Property damage only (PDO) were predominant (95.98%) among the recorded traffic events compared to traffic events (4.02%). The most frequent traffic events included rear-end collisions, driving into an obstacle, side-impacts and overturning. To some extent, they can be classified as intermediate between classical types of traffic events occurring on single-lane and two-lane roundabouts. The most frequent causes of the traffic events were: not-giving way, excessive speed with respect to the conditions on the road, lack of safe distance from the preceding vehicle, illegally changed lanes, illegal overtaking.

The analysis shows that the drivers in turbo roundabouts with lane dividers in the form of a single continuous line often change traffic lanes illegally, thus crossing the single continuous line. Consequently, this leads to the occurrence of side impacts caused by the change of the traffic lane. The analysis of the data shows that some 56% of all the road collisions¹ in these roundabouts are side impacts (Fig. 2). This situation took place e.g. in two turbo roundabouts in Konin which were not included in the analysis since both intersections were accepted for the use in July 2012 and, to date, the only road traffic collisions occurred during changing road lane illegally. Similarly in the roundabout in Rypin (Kuyavian-Pomeranian Voivodeship), which was accepted for the use in 2011. Other types of road collisions according to the frequency are: rear-end collisions (ca. 34%), hitting obstacles or road sign (ca. 6%), hitting pedestrian (ca. 2%), capsizing the vehicle (ca. 1%) and others (ca. 1%).

Furthermore, the analysis of the structure of road accidents² (Fig. 3) confirms the information presented in the related literature since multi-lane roundabouts are not safe solutions for vulnerable road users. In the turbo roundabouts studied, as many as 50% of the accidents that occurred were hitting pedestrians. Other types of accidents that occurred in turbo roundabouts were side impacts (ca. 33%) and rear-end collisions (ca. 17%). It should be emphasized that the contribution of road collisions was ca. 93% while the contribution of road traffic accidents was merely ca. 7%.

In the case of traffic events which involve vehicles and unprotected road traffic participants, it is pedestrians and cyclists who are usually the most seriously injured. Since driving into pedestrians was

the most numerous group of road traffic accidents, the contribution of the seriously injured persons³ as a result of traffic events amounts to ca. 65%. The percentage of slightly injured persons⁴ is ca. 35%, whereas no fatalities were reported in these locations during the period studied⁵. The percentage of the injured according to the degree of injury is presented in Fig. 4.

Another analysis concerned the structure of the involved in the traffic events according to the nature of their participation. The involved it means a person who participate in a traffic events whose property was damage and/or health status was deteriorated. Due to the fact that typical traffic events in the turbo roundabouts studied were side impacts and rear-end collisions of cars, the most of the involved were car drivers (ca. 90%). A fraction of the injured cyclists was ca. 7% whereas the fraction of pedestrians involved was ca. 3% (Fig. 5). A comprehensive structure of causes of traffic events was presented in Fig. 6.

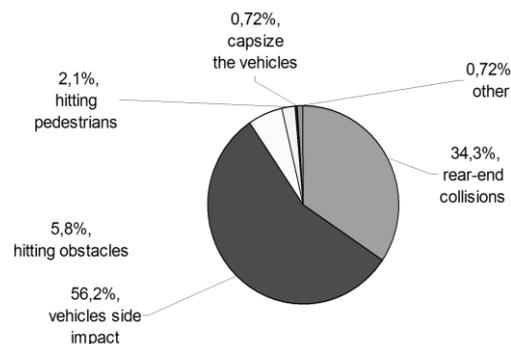


Fig. 2. Structure of road collisions on turbo roundabouts with traffic lane separators as a single continuous line P-2 type

¹ Road collisions occur when road traffic is suddenly disturbed. A series of events usually follow and they end up in a state when the traffic of collision participants cannot be continued according to the previous assumptions. Not all the traffic disturbances are collisions (e.g. traffic jams).

² Road accident is understood to mean a road traffic collision which involved injured persons among road users.

³ According Polish regulations presented in Komenda Główna Policji (2006) - a seriously injured person means a person who suffered from the following types of injuries: fractures, concussive traumas, damages in internal organs, slashes and lacerated wounds, overall serious shocks that necessitates medical intervention, all other injuries that require hospitalization.

⁴ According Polish regulations presented in Komenda Główna Policji (2006) - a slightly injured person means a person who suffered from the following types of injuries: joint dislocations, contusions, scratches and abrasions but they received the medical treatment.

⁵ According Polish regulations presented in Komenda Główna Policji (2006) - the fatality is understood to mean a person who died at the scene of the accident or within 30 days following the accident as a consequence of the bodily injuries.

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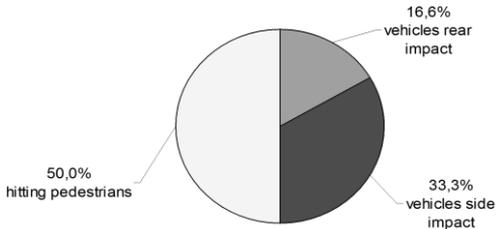


Fig. 3. Structure of road accidents on turbo roundabouts with traffic lane separators as a single continuous line P-2 type

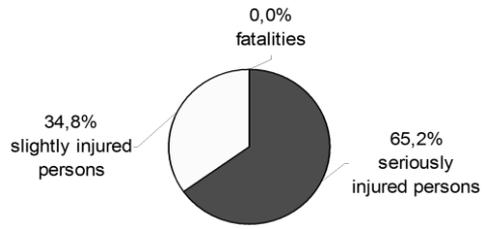


Fig. 4. Percentage shares of injured persons in traffic events (according to severity) on turbo roundabouts with traffic lane separators as a single continuous line P-2 type

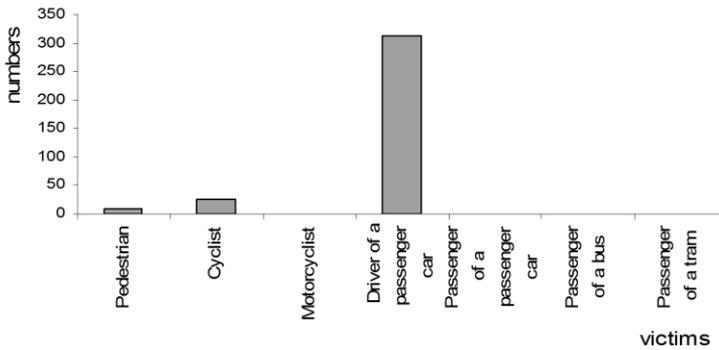


Fig. 5. Number of victims (according to the nature of participation) on turbo roundabouts with traffic lane separators as a single continuous line P-2 type

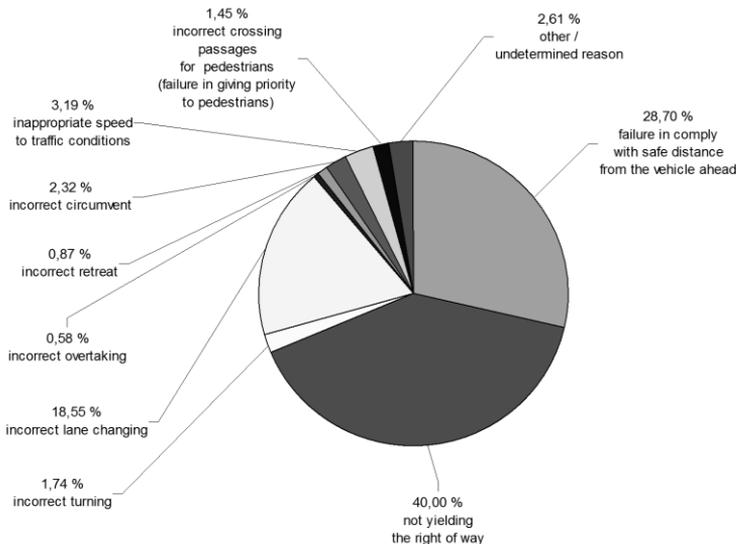


Fig. 6. The structure of causes of traffic events on turbo roundabouts with traffic lane separators as a single continuous line P-2 type

Analysis of the structure of causes of traffic events showed that 1% of these events were caused by pedestrians (this was mainly due to crossing the road illegally). Other ca. 99% were caused by drivers. Analysis of the structure of the traffic events caused by the drivers shows that the most frequent causes were: non-giving way (40%), lack of safe headway from the preceding vehicle (ca. 29%) and illegally changed lanes (ca. 19%).

5. The comparison of road safety on turbo roundabouts in Poland with raised lane separators and on turbo roundabouts with traffic lane separators as a continuous line P-2 type

From the practical point of view, it seems essential to investigate the differences in the nature of traffic events occurring in turbo roundabouts with raised lane dividers as compared to turbo roundabouts with traffic road dividers in the form of a single continuous line. This type of comparison of the statistical data concerning traffic events that occurred in turbo roundabouts in Poland in 2010-2012 is presented in Table 2. A relatively small sample that was used for drawing the conclusions presented in this study results from the fact that turbo roundabouts are a new solution in Poland. Furthermore, it should be noted that they are characterized by a generally high level of road safety for the users, thus the number of the events that have occurred so far is very low.

Comparison of the road safety in the two groups of turbo roundabouts located in Poland presented in Table 2 leads to the following conclusions:

- both groups of turbo roundabouts ensure a high level of road safety to their users. In the locations studied, road traffic collisions ranged from 93 to 96% of all the traffic events, whereas traffic accidents ranged from 4 to 7%. No fatalities were reported in the period of the study,
- turbo roundabouts with raised lane dividers are solutions which are safer than turbo roundabouts with lane dividers in the form of a single continuous lane (because e.g. on turbo roundabouts with traffic lane separators as a single continuous line were greater number of road events in total number of road accidents),
- the most frequent traffic events in turbo roundabouts with raised lane dividers included rear-end collisions, driving into an obstacle, side-

impacts and overturning. To some extent, they can be classified as intermediate between classical types of traffic events occurring on single-lane and two-lane roundabouts,

- the most frequent events in turbo roundabouts with traffic lane dividers in the form of a single continuous line were side impacts, rear-end collisions, driving into pedestrians and driving into obstacles. The level of road safety recorded in these roundabouts did not differ considerably from the one discussed in the literature (e.g. in the studies (Kimber, 1980; Macioszek, (2012b)) for the two-lane roundabouts,
- causes of traffic events in both types of turbo roundabouts were similar and they mainly concerned: non-giving way, excessive vehicle speed with respect to the conditions,
- on the road, lack of safe distance from the preceding vehicle, illegally changed lanes, illegal overtaking. Furthermore, some events caused by non-giving way to pedestrians were reported in turbo roundabouts with traffic lane dividers in the form of a single continuous line.

6. Summary and conclusions

According to the studies carried out abroad (e.g. in the Netherlands, Belgium or France), the roundabouts, compared with conventional intersections, cause a considerable reduction in the number of dangerous traffic events i.e. collisions (30% to 60%), accidents with injured persons (40% to 90%) and fatalities (70% to 95%). It is very important that this type of intersection improves road safety of not only drivers and their passengers, but also pedestrians in single-lane roundabouts. Roundabouts eliminate or reduce the number of such traffic events as head-on collisions, collisions during turning left, right side impacts or driving into pedestrians. A relatively new type of roundabouts in Poland, i.e. turbo roundabouts, has been regarded in the world as a solution that is safer than multi-lane roundabouts, which is mainly due to the raised lane dividers. With respect to road safety, the raised lane dividers in turbo roundabouts are very important. The analysis of the traffic events in turbo roundabouts with lane dividers in the form of a single continuous line helped formulate the following conclusions:

Table 2. The comparison of road safety on turbo roundabouts operating in Poland with raised lane separators and on turbo roundabouts with traffic lane separators as a continuous line P-2 type

		Turbo roundabout	
		with raised traffic lane separators	with traffic lane separators as a single continuous line P-2 type
Number of analyzed roundabout		7	10
The share of road collisions in total number of traffic accidents		~ 96 %	~ 93 %
The share of road events in total number of road accidents		~ 4 %	~ 7 %
Road collision structure		- vehicles rear impact (~ 33 %), - invade on obstacle (~ 30 %), - vehicles side impact (~ 24 %), - overturning of vehicle (~ 5 %), - others (~ 8 %).	- vehicles rear impact (~ 34 %), - invade on obstacle (~ 6 %), - vehicles side impact (~ 56 %), - overturning of vehicle (~ 1 %), - others (~ 1 %), - invade on pedestrians (~ 2 %).
Road events structure		- vehicles rear impact (~ 86 %), - vehicles side impact (~ 14 %).	- vehicles rear impact (~ 17 %), - vehicles side impact (~ 33 %), - invade on pedestrians (~ 50 %).
Structure of injured persons in traffic events (according severity)	slightly injured persons	~ 55 %	~ 35 %
	seriously injured persons	~ 45 %	~ 65 %
	fatalities	0 %	0 %
Structure of victims (according nature of participation)	drivers	100 %	~ 90 %
	cyclists	0 %	~ 7 %
	pedestrians	0 %	~ 3 %
Structure of causes of traffic events	by pedestrians	0 %	~ 1 % (involved those pedestrians, who crossing the road in prohibited places)
	by vehicles drivers	100 %	~ 99%
Structure of causes of traffic events which result from the fault of vehicles drivers		- not yielding the right of way (~ 33%), - inappropriate speed to traffic conditions (~ 25%), - failure in comply with safe distance from the vehicle ahead (~ 23%), - incorrect lane change (~ 16%), - incorrect circumvent (~ 1%), - incorrect overtaking (~ 1%), - others (~ 1%).	- not yielding the right of way (40%), - inappropriate speed to traffic conditions (~ 3%), - failure in comply with safe distance from the vehicle ahead (~ 29%), - incorrect lane change (~ 19%), - incorrect circumvent (~ 2%), - incorrect overtaking (~ 1%), - others/undetermined reasons (~ 3%), - incorrect crossing passages for pedestrians (failure in giving priority to pedestrians) (~ 2%), - incorrect retreat (~ 1%).

Source: own study based on Macioszek (2012c, 2012d, 2012e).

- no fatalities were reported during the period of the analysis. Road traffic collisions were predominant (93%) among the recorded traffic events compared to traffic accidents (7%),
- this type of roundabouts are not safe for the unprotected road users since as much as 50% of road accidents were driving into pedestrians,
- road accidents in the form of side impacts of the vehicles represented 33%, whereas rear-end collisions were ca. 17%,
- the most frequent road traffic collisions were side impacts (ca. 56%) and rear-end collisions (ca. 34%),

the most frequent traffic events were: non-giving way (40%), lack of safe distance from the preceding vehicle (ca. 29%) and illegally changed lanes (ca. 19%).

Furthermore, the comparative analysis concerning the level of road safety between turbo roundabouts equipped in raised lane dividers and turbo roundabouts with lane separators in the form of continuous line revealed that turbo roundabouts with raised lane dividers are safer solutions than turbo roundabouts with traffic lane dividers in the form of continuous line. In turbo roundabouts with lane dividers in the form of a single continuous line, the level of road safety does not much differ than the level of road safety that occurred in two-lane roundabouts. Turbo roundabouts have been used in Poland since recently. Thus it is difficult to verify unequivocally whether the level of road safety is comparable with two-lane roundabouts because the drivers might not have been accustomed to this type of roundabouts yet or they consciously violate the traffic code regulations by e.g. crossing the continuous line illegally. Furthermore, based on the literature survey and the results of the analyses presented in this paper, one can conclude that replacing the raised lane dividers with a single continuous line of P-2 type does not cause considerable improvement in road safety in the area of the intersection.

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