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Performance and Safety of Roundabouts with Traffic Signals

Marian Tracz^{a,*}, Janusz Chodur^a

^a *Cracow University of Technology, Institute of Road and Railway Engineering, Warszawska Str. 24, 31-155 Krakow, Poland*

Abstract

The paper presents designs, advantages and some drawbacks of various layouts of roundabouts with traffic signals, used in urban arterials on crossings with large traffic volumes. The authors analyze signal settings with alternative phasing used at intersections that can provide the intersection capacity of about 6500 veh/h in 2x2 lanes arterials or even 8000 veh/h in 2x3 lanes arterials. Accident statistics for roundabouts with traffic signals in Krakow are also given and discussed. In addition, presented are practical examples of changes of signalized roundabouts geometry; reconstruction into a form of turbo-roundabout and its effects regarding traffic safety and good performance.

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1. Introduction

Roundabouts with traffic signals are fairly common in urban and suburban areas of Polish cities, particularly the so-called “intersections with a central island”. One characteristic feature of their geometry is a tangential entry design, i.e. the axis of each entry and exit are tangential to the axis of the circulatory roadway around the central island. Such roundabouts are characterized by crossing maneuvers instead of merging, diverging and weaving maneuvers – typical of classic large roundabouts. The main feature of the analyzed roundabouts is that they work with two-phase traffic signals (Fig. 1). The left turning capacity is determined by storage areas around the central island and by the cycle length. In their design there is a close link between the geometry of the roundabout, traffic control and signal settings parameters. One frequent design and operational problem of such roundabouts with two-phase signal settings involves a collision between the needs of pedestrian movement and the capacity of left-turn movement. In optimization of the central island diameter, a probabilistic description of vehicle cyclic arrivals

* Corresponding author. Tel.: +0-48-12-6282320 ; fax: +48-12-6282328 .
E-mail address: mtracz@pk.edu.pl

cycles is used. In the paper, a diagram helping to select the central island diameter and/or cycle length at known or predicted left-turning traffic flows is presented.

In order to eliminate overloading of the internal storage spaces of the existing roundabouts with traffic signals, a new multiphase traffic signal control system has been installed. The paper presents a comparison of the efficiency of two- and multiphase traffic signal settings with the operation of channelized intersections with multi-phase traffic signals. The operation of signalized roundabouts was also compared with the operation of classic two-lane roundabouts with no traffic signals.

Accident statistics indicate that roundabouts with traffic signals do not rank amongst the safest in Krakow. One such intersection, accommodating noticeable public transport (buses and trams) flows was rebuilt into the so-called turbine-roundabout to enhance its traffic safety and performance, what is presented in the paper..

2. Characteristics of roundabouts with traffic signals

The geometric scheme of a roundabout with traffic signals is presented in Fig 1.

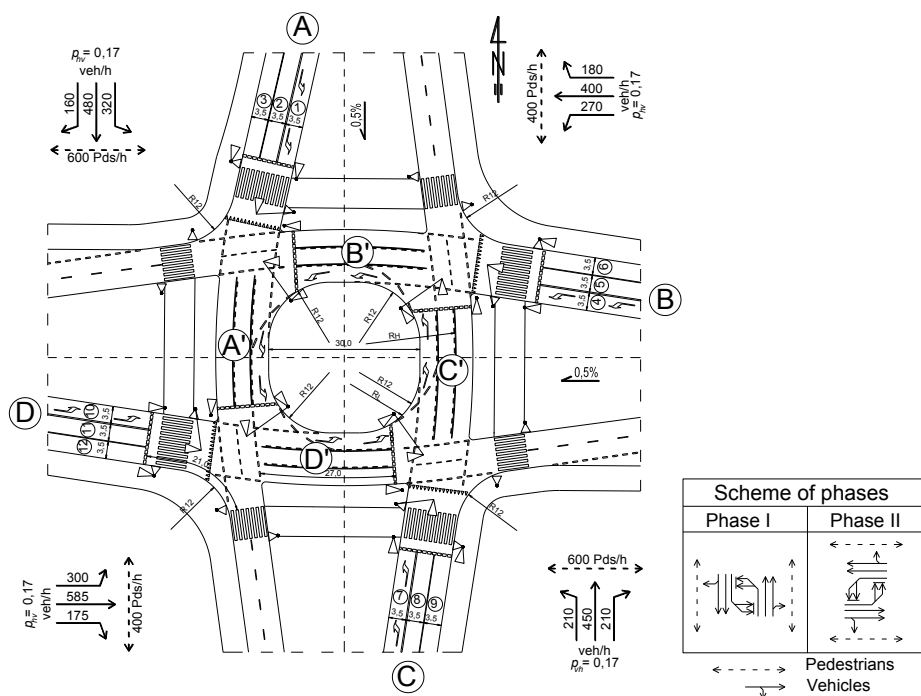


Fig. 1. Scheme of a roundabout with traffic signals.

A roundabout with traffic signals has channelized entries and internal storage areas (accumulation bays) where vehicles turning left wait for their green light, which allows their non-conflict operation. Usually the internal storage areas can provide capacity of left-turning movement from 250 to 600 pcu/h depending on the signal cycle length and size of this area, which depends on the central island diameter and the number of traffic lanes within the area. Roundabouts with traffic signals can reach very high total capacity by increasing the number of lanes at entries and within intersection. Beside high capacity, including high capacity of left-turning movement, the

described roundabout also offers high performance in terms of delay at operation with simple two-phase traffic signals, and also at different phasing. However, it requires a large area.

According to the Polish guidelines [1]:

- the central island can be oval in shape determined by horizontal curves of intersecting one-way roadways and by curves for left-turning movement, or the shape of a circle (Fig. 1). The diameter of the central island in the range of 30 - 50 m is recommended,
- it is recommended that the diameter of the curve on a single-directional road passing through the intersection should be selected so as to ensure that the tangential does not extend behind the stop lines on the entries to the intersection. It is recommended that the radius should range within $R_H = 150 - 300$ m. Turning radius R_L for left-turn movement should not be less than 10 m,
- it is recommended to use separate lanes for left and – where necessary – right turning movements – depending on traffic flow demands. The number of straight-through lanes should be the same as on the street sections before intersection and behind it,
- the number of lanes on the storage area on extension of a given primary entry should be equal to the number of through- and left-turning lanes,
- if a tram line goes through the central island, the island diameter should allow for its stop on the island without it blocking the traffic from the storage areas.

3. Selected problems of signalized roundabouts design

In selecting the geometrical parameters of signalized roundabouts the same criteria are taken into consideration as for other at grade intersections, i.e.: traffic safety, traffic performance, adjustment to the needs of vulnerable road users, minimization of environmental impacts and economy. Traffic performance of signalized roundabouts is attained when adequate capacity is ensured, and when there is no overloading of storage areas for pedestrian and vehicular road users and under conditions of required LOS.

Accommodation of the requirements of pedestrian and cycle traffic demands means in practice providing convenient conditions for crossing the street and shortening the waiting time for the green signal. Designing the geometry and signal settings at an intersection should be conducted and optimized simultaneously.

What is important in ensuring the efficiency of the roundabout with traffic signals is the storage areas dedicated to left-turning movements. One natural issue that emerges in the course of designing the central island diameter involves a conflict between the demands of vehicular and pedestrian traffic flows. Increasing the distances which pedestrians have to cross when the entries are widened, requires long cycle time, whereas the capacity of left-turning movement depends on the product of the number of cycles per hour and the number of places for vehicles in the storage area. Consequently, pedestrians are frequently required to walk in two stages, which results in shorter cycle time.

In the analysis of the volume of the left-turning traffic flow, a probable number of vehicles gathering in the storage area within one phase can be calculated. This number of vehicles should not exceed the storage capacity of the area, which can be described by the following inequality:

$$F_s \geq N_{\max} \quad (1)$$

where:

- F_s – storage areas on straight lanes within the internal storage area [pc], $F_s = \frac{l_s}{L} \cdot n_l$,
- l_s – length of the storage area [m],
- L – average length of the post for one vehicle [m],
- n_l – number of lanes,

N_{max} – probable maximum number of passenger cars gathering within the storage area in the signal cycle T , determined on the basis of their average number $N_{av} = \frac{V_L \cdot T}{3600}$, under the assumption of Poisson distribution of arrivals and at 95% probability (fourth and first quadrants of the nomogram in Fig. 2).

After a transformation of the inequality (1). the relationship between the length of storage area l_a and the maximum number of vehicles gathering within the storage area N_{max} can be obtained (second quadrant of the nomogram in Fig. 2):

$$l_a \geq \frac{N_{max} \cdot L}{n_l} \tag{2}$$

On the basis of the above assumption, and further assuming that the storage area length lies within the range of the central island diameter ($0,9 \div 1,0$), and that it depends on the location of the signaling post (third quadrant of the nomogram in Fig. 2), a diagram was developed to facilitate the selection of central island diameter or the signal cycle length (Fig. 2).

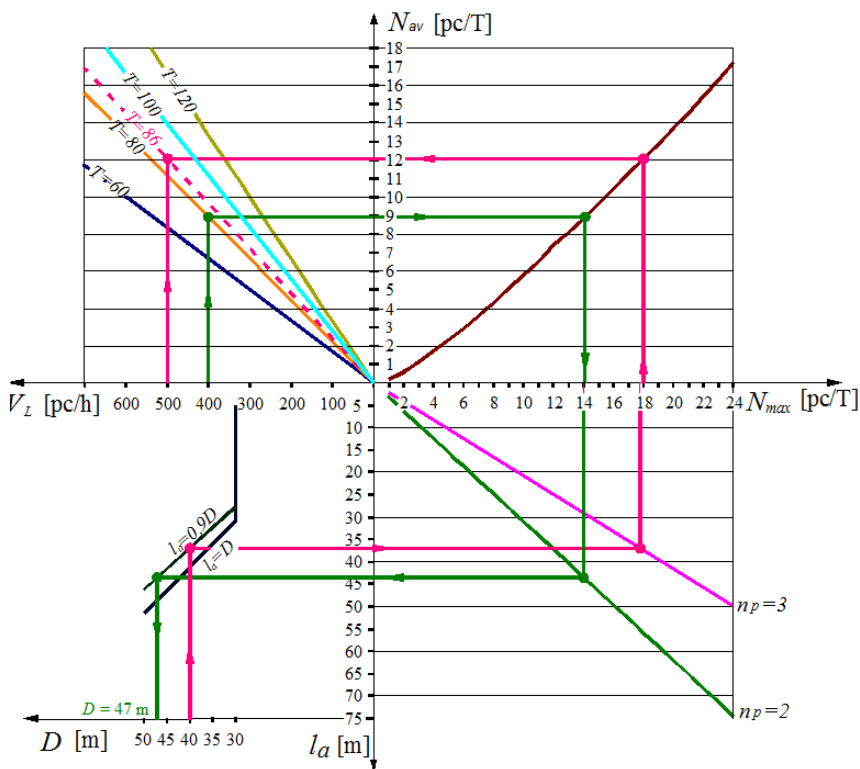


Fig. 2. Diagram for selection of central island diameter

The relationships which gave a basis for development of the monogram have the analytic nature. Empirical observations have confirmed correctness of the assumed description. In design an important role plays conversion of real into equivalent (cars) vehicles and adoption of the average length of the post for one vehicle on the internal storage space.

Figure 2 also presents a method for determination of the diameter of the central island and the length of the cycle time. For example, for the assumed traffic volume of left-turning movement $Q_L = 400$ pc/h (green line) at the signal cycle length $T = 80$ s, the diameter of the central island at $n_l = 2$ should be a minimum $D = 47$ m. Similarly, with the diameter of the central island $D = 40$ m (red line) and $n_l = 3$, the required signal cycle length can be determined to be $T \approx 86$ s, which guarantees that the internal storage area is not overloaded at the assumed traffic volume of the left-turning movement $Q_L = 500$ pc/h.

4. Analysis of operational performance of two-phase and multiphase traffic signaling

The roundabouts with traffic signals installed at the beginning of their operation were designed to work in situations of two-phase traffic signal settings. Increasing traffic flow volumes in urban areas resulted in situations when this simple two-phase operation did not guarantee good performance of such roundabout operation. Usually the problems began with overloading of the internal storage areas by left-turning vehicles. Hence the demand for multiphase traffic signal settings that can limit the signalized roundabout blocking from the internal storage areas. Below the results of a comparative analysis of a signalized roundabout operating with two-phase and multiphase traffic signal settings, real and modeled intersections, are presented. In this analysis, the Polish capacity calculation method has been used [2]. The layout of the signalized roundabout (located in the city of Rzeszow) is shown in Fig. 3. The traffic volumes in morning and afternoon peaks are shown in Fig. 4.

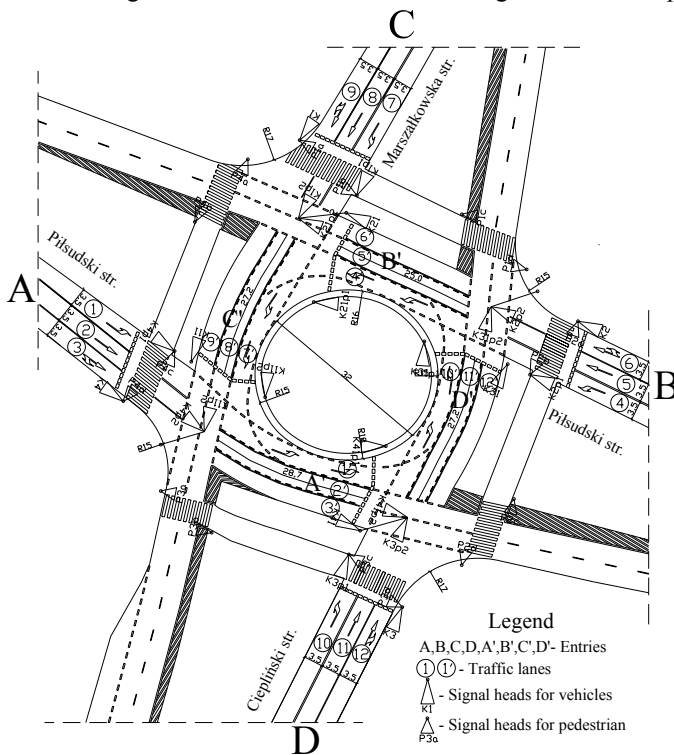


Fig. 3. Geometrical layout of the intersection in the city of Rzeszow.

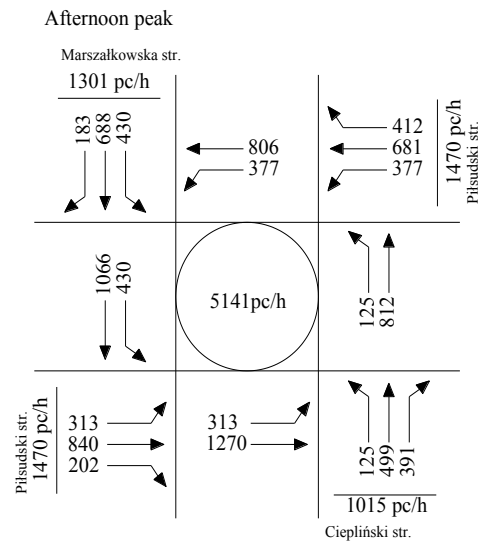


Fig. 4. Design traffic volumes for signalized roundabout as in Fig. 3

The traffic signal phasing and the program of two-phase signal settings are presented in Figs 5 and 6. In such designs the internal storage areas were often overloaded. Therefore multiphase signal control systems presented in

Fig. 7 were suggested by designers. In these analyses of performance the classic two-lane roundabout (without traffic signals) with the inscribed circle diameter equal to diameters of signalized roundabouts (case III) was also included. In this example the bypasses for right-turning were provided. In the analysis of the capacity and traffic performance of a roundabout without traffic signals, a method developed by the authors (recommended by the Polish General Directorate of National Roads) was used (Table 1). It is based on the results of empirical measurements described in [3, 4, 5].

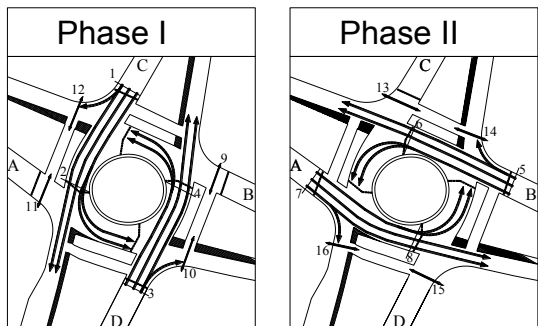


Fig. 5. Signal phasing at signalized roundabout as in Fig. 3.

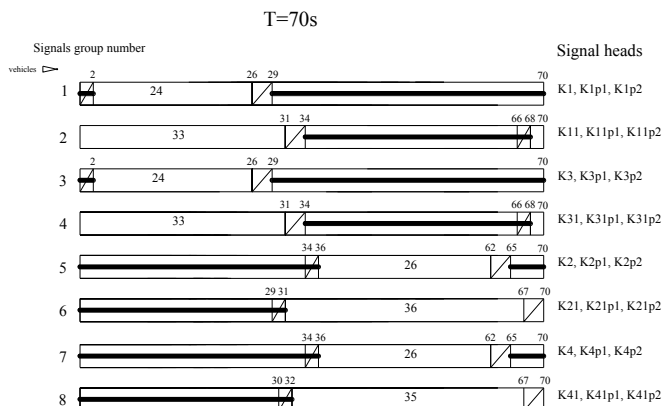


Fig. 6. Fixed time signal settings at the intersection presented in Fig. 3. (pedestrian signal groups were ignored)

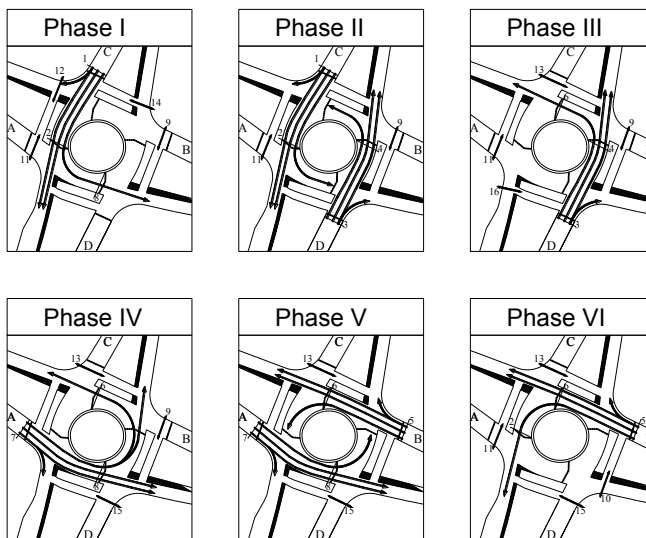


Fig. 7. Proposed phasing at the intersection presented in Fig. 3

On the basis of calculation results of capacity and traffic performance measures, it can be stated that after implementation of multiphase control, the performance of the intersection declined as:

- in the case of a 2-phase control, the total intersection capacity is 20% higher if the internal storage areas are not overloaded,
- the use of a 6-phase control in comparison with a 2-phase control V/C rates can increase at primary entries even by 26%, and also the vehicular delay can considerably increase,
- 2-phase control does not comply with the requirement of not overloading the internal storage areas by left-turning vehicles due to excessively long signal cycle and/or limited internal storage areas,
- 6-phase control can cause worse traffic performance in both traffic peaks, but can eliminate overloading of the internal storage areas.

Table 1. Comparison of traffic performance measures for the intersection presented in Fig. 6 with 2- and 6-phasing and unsignalized two-lane roundabout

Capacity and performance measures	Case			Absolute difference		Relative difference	
	I signalized (2-phase control) $T=70$ s	II signalized (6-phase control) $T=90$ s	III unsignalized Rbt	II to I	III to I	II to I	III to I
Intersection capacity [veh/h]	6628	5230	4022	-1398	-2606	21%	39%
Critical flow rate to capacity ratio V/C [-]	0,78	0,98	1,28	0,20	0,50	26%	64%
Average overall intersection delay [s/veh]	29	113	692	84	663	290%	2286%

Two-lane roundabout (case III) at the analyzed traffic demands does not guarantee the required capacity and can generate very large delays. Further analyses were conducted for the modeled roundabout layout with traffic signals (total traffic volume at intersection was 5000 veh/h and left turning movement from entry A was 600 veh/h), and also for comparison for normal roundabout and such roundabout with bypasses. Results of this analyses gave the basis for the following conclusions:

- the use of a 2-phase traffic signal control can guarantee the highest intersection capacity on condition that risk of overloading of the internal storage areas is very low,
- the use of 2-phase traffic signal settings with a sub-phase can provide efficient operation of the intersection without the risk of overloading of the left turns from entry A ($V = 600$ veh/h) limited by the size of the storage area (entry D'). However, this design decreases the total capacity of the intersection by 20%, causing an increase of average delay by about 50%,
- the performance of an intersection with a 3-phase control is the lowest. With this control, the total intersection capacity drops by 33% and average delays increase nearly twofold,
- at similar traffic volumes, an unsignalized two-lane roundabout does not guarantee the required total capacity even after building bypasses for large right-turning movements.

The comparisons show much higher capacities of the signalized roundabout in comparison with a two-lane roundabout without traffic signals.

5. Traffic safety at signalized roundabouts

In Krakow from a few decades operate 11 roundabouts with traffic signals. Regarding safety (number of accidents and collisions per one million vehicles a year) the most important of these roundabouts located on main urban arterials are situated among 25 most dangerous intersections with traffic signals (out of 230). Figures 8 and

9 show the statistics of road collisions and accidents at roundabouts with traffic signals in Krakow in the period of 2000-2011.

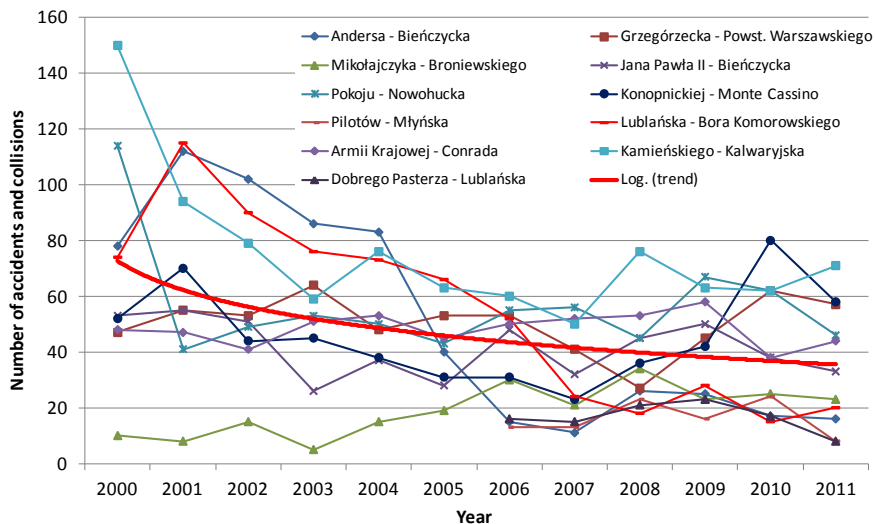


Fig. 8. Annual numbers of accidents and collisions at signalized roundabouts in Krakow in the period of 2000-2011

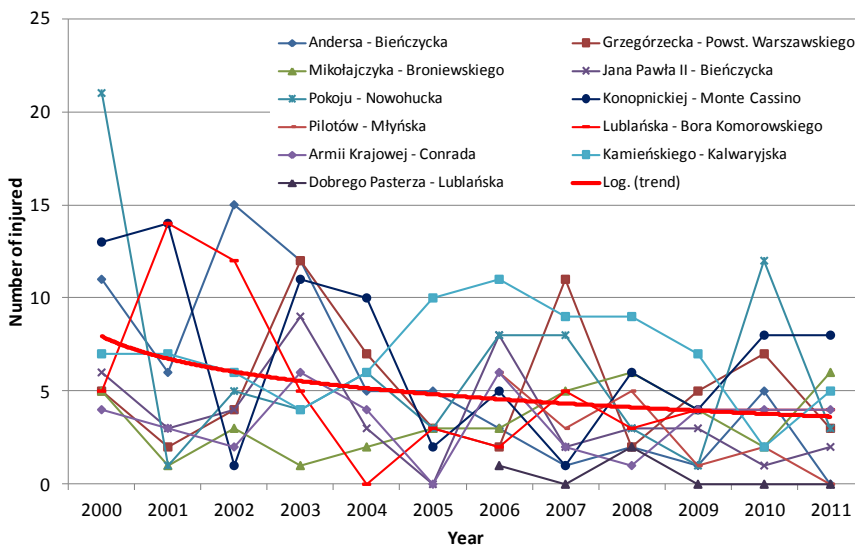


Fig. 9. Annual numbers of injured at signalized roundabouts in Krakow in the period of 2000-2011

On the basis of available statistics, the following conclusions can be drawn:

- The traffic volumes at signalized roundabouts in urban areas are in the range of 4500 – 6500 veh/hour in peak periods (7.00-9.00 and 14.00-17.00),

- The number of accidents and collisions as well as the number of persons injured at signalized roundabouts in Krakow show a decreasing trend, despite a significant increase in traffic volumes,
- The number of persons injured is very similar to the number of accidents and show fluctuations typical of a small number of events,
- A certain increase in the number of persons injured can be seen in 2005 due to new rules of designing intergreen periods at signalized roundabouts (with time offset between primary entries and secondary entries – from the storage space at central island – on extension of basic entry).

Unsatisfactory state of traffic safety stimulates a search of designs to improve this state on signalized roundabouts . One of proposals is a reconstruction of typical signalized roundabout geometry into a form of the turbine roundabout .

6. Signalized turbo roundabouts

In order to change tram lines alignments and function of south Grzegórzeckie roundabout entry, the intersection geometry was reconstructed into a form of so-called turbo roundabout (Figs 10 and 11) with traffic signals. The new form was to ensure that the island layout accommodates trams within the central island (tramcars 32 m long) and vehicles on the lanes within the internal storage areas and to provide improvement of traffic safety. This design has by much larger internal storage areas within the new roundabout which, as the signalized roundabout with a central island described earlier, also allows traffic control based on a simple quasi 2-phase control. Shared lanes and bus-tram stops were designed.

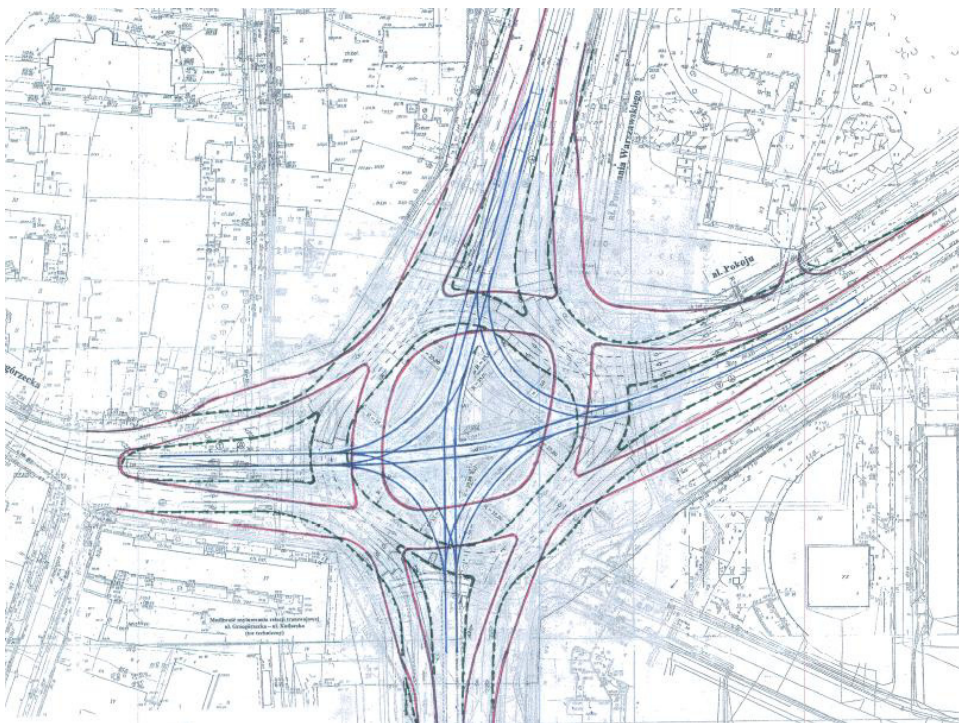


Fig. 10. Differences in the design of intersection areas; solid red line– signalized roundabout with a central island (before), dotted green line– new turbo roundabout [6]



Fig. 11. Grzegórzeckie roundabout after reconstruction (photo: W. Majka UM Krakow)

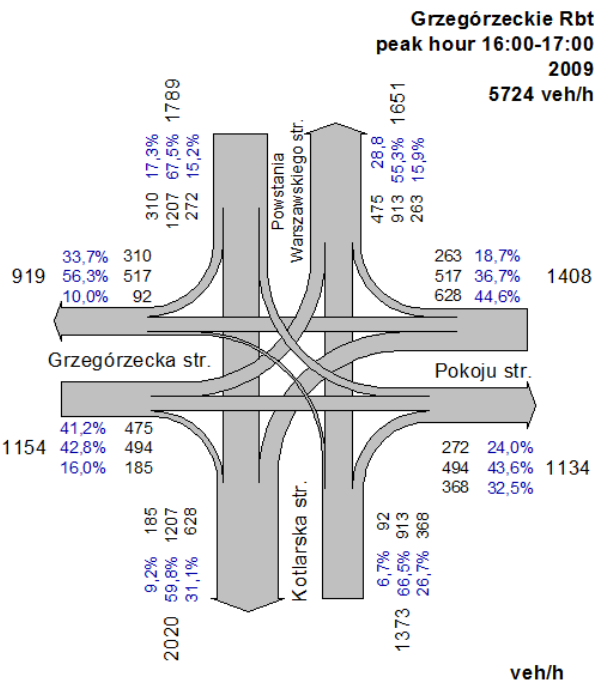


Fig. 12. Traffic volumes at Grzegórzeckie roundabout

The design of a turbo-roundabout is based on the minimum internal radiuses of 25 m (for left-turning traffic) and 30 m, 35 m for straight-through movement. The present capacity with vehicle actuated signals with priority for public transport is approx. 6000 pcu/h during the afternoon peak. Fig. 12 shows a diagram of traffic intensity at the intersection.

Road incidents data for the period of 2003-2009 at the intersection are presented in Table 2.

Table 2. Number of accidents and collisions before and after the reconstruction of Grzegórzeckie roundabout

YEAR	ACCIDENTS and COLLISIONS (A&C)	ACCIDENTS	INJURED	KILLED	PEDESTRIANS RUN INTO	A&C INVOLVING TRAMS AND BUSES	SIGNAL
before reconstruction							
2003	64	11	12	0	3	7	22
2004	48	5	7	0	1	8	14
2005	53	3	3	0	2	4	18
2006	53	2	2	0	1	7	15
2007	41	8	11	0	2	1	15
year of reconstruction 2008							
2008	27	2	2	0	2	3	5
after reconstruction							
2009	45	5	5	0	3	2	6
2010	62	6	7	0	4	5	13
2011	57	3	3	0	0	0	13

The overall number of incidents and traffic signals-related incidents (running into the rear bumper of the preceding vehicle) in comparison with the average number before the reconstruction is at similar level, however their severity is lower declined. The time span after the reconstruction is too short for any generalizations.

Similar reconstruction was realized also at another roundabout (Kocmyrzowskie roundabout). Prior to the reconstruction, the intersection was known as a high risk site, for incidents both in terms of the general number of road collisions and accidents, number of accidents involving (hitting) pedestrians, incidents involving municipal transport vehicles and the so-called traffic signals-related incidents. Additionally, in terms of the traffic progression from minor entries and internal storage areas, and also movements of trams (tram tracks occupy the central island) the traffic performance was very poor resulting from limited capacity of the entries. This in turn had a serious impact on traffic safety. The intersection has a high share of left-turning traffic, practically from all entries in the range of 240 – 320 veh/h. The operation time of Kocmyrzowskie roundabout following its reconstruction allows reliable evaluation of changes in road traffic safety (Table 3). As indicated by the data, there has been a marked improvement in road traffic safety both in terms of the overall number of incidents and, above all, in terms of accidents and victims, collisions involving public transport vehicles and the so-called signals-related ones. Thus it can be stated that the effectiveness of the new geometric layout and traffic signals at the intersection are very favorable.

Table 3. Number of accidents and collisions before and after the reconstruction of Kocmyrzowskie roundabout (3820 veh/h)

YEAR	ACCIDENTS and COLLISIONS (A&C)	ACCIDENTS	INJURIES	KILLED	PEDESTRIANS RUN INTO	A&C INVOLVING TRAMS AND BUSES	SIGNAL
before reconstruction							
2000	78	11	11	0	10	8	19
2001	112	5	6	0	1	10	17
2002	102	14	15	1	9	11	20
2003	86	11	12	0	11	10	21
2004	83	4	5	0	4	12	20
year of reconstruction 2005							
2005	40	5	5	0	4	4	4
after reconstruction							
2006	15	3	3	0	3	3	3
2007	11	1	1	0	0	2	2
2008	26	2	2	0	1	4	3
2009	25	1	1	0	1	2	2
2010	19	5	5	0	0	0	0
2011	16	0	0	0	0	0	0

When comparing both similar roundabouts, much higher number of collisions (no victims) at the first roundabout can be seen. Impact on higher risk can have; much larger traffic volumes at high speed on both NS arterials approaching roundabout, and simultaneously tighter geometry (use of too small curve radii for these straight movements), i.e. lack of design homogeneity.

7. Conclusions

High volumes of left-turn movements favor the use of roundabouts. Under the conditions of heavy traffic intensity at an intersection, roundabouts may operate effectively with traffic signal control. In Poland, signalized roundabouts have been constructed for about 40 years. When used with simple two-phase signals, they facilitate collision-free movement of left-turn vehicles due to the possibility of storage of vehicles within the internal storage space. The principal design problem involves the selection of appropriate parameters of geometry and control which would complement traffic intensity at the intersection. Under the basic arrangement involving two-

phase signals, the capacity of the internal storage area must, to a high level of probability, be able to accommodate stopping left-turning vehicles within the intersection so that they do not block the intersection. In the case of the existing signalized roundabouts, an increase of traffic volumes may cause overloading of internal storage areas. This problem can be solved by the use of multiple-phase signals. This entails, however, a decline in the overall capacity of the intersection and deterioration of traffic performance on entries. Signalized roundabouts have much larger capacity than classic unsignalized two-lane intersections, and the rule applies regardless of the signalized design used.

The geometry of the Polish type of signalized roundabout, similar to several American two-lane roundabouts (tangential design), as entries are tangential to the central island. Such roundabout can be crossed at high speeds, which increases accident risk.

Secondary entries (from storage areas) opened sooner in order to improve progression from the primary entry can lead to an increase in the probability of accidents.

The need for improvement in road traffic safety and the efficiency of internal storage areas has led to the construction of signalized turbo roundabouts also in Poland. The first impressions indicate an improvement in the safety after their reconstruction and further point out higher general efficiency even under the conditions of higher accident risk of means of public transport (buses and trams) stopping at bus/tram stops within the intersection.

Acknowledgements

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