Signalized Turbo Circle; design and performance

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ABSTRACT

A roundabout or traffic circle equipped with leg-by-leg traffic control should not be regarded as a robust solution, because of the accumulation of unnecessary waiting time. Two-phase control is a better alternative. Therefore the design should be adjusted by enlarging and changing the shape of a roundabout. This study considers a signalized traffic circle of a moderate size, with a diameter of 105 m. It will have radially connecting approach legs –to reduce the entry speed– and the departure legs that exit the roundabout tangentially, to create space for queuing left-turn vehicles. The resulting shape is called a Turbo Circle. To tailor a traffic circle expressly to the application of two-phase controlled traffic lights, left-turn and through going directions should be separated.

In the design of the Turbo Circle, mountable, elevated guide islands are recommended to avoid cut-off turns.

An analytical model has been developed to compare the cycle lengths of a Turbo Circle and a four-leg crossroads, with the same number of lanes, i.e. two per direction. From this it may be concluded that a Turbo Circle with a diameter of 105 m proves its usefulness in situations with high traffic volumes. Above 6,000 pcu/h, the cycle length of a Turbo Circle tends to be less than half that of a four-leg crossroads, resulting in substantially less delay. The total capacity will thus also be higher, provided that opposing left turn volumes are not more than 130% to 160% of the through-going volumes from the same legs.
1 INTRODUCTION

This paper deals with the problem how to create a signalized traffic circle which can handle a substantial amount of left-turn traffic under the condition of a limited diameter.

If a roundabout has a small diameter (outer diameter up to approx. 60-70 m), traffic cannot queue on the roundabout itself, because the roundabout segments are too short. In such cases, only the following traffic control methods can be used:
- full signalization with leg-by-leg control (also called split phasing);
- roundabout metering signals on selected approaches.

A simple explorative study shows that roundabouts are too small to be equipped effectively with permanently operating traffic lights. That is why metering signals are sometimes used at compact two-lane roundabouts.

To use full signal equipment effectively, it is necessary to enlarge and change the shape of a roundabout. Generally, these enlarged signalized roundabouts are called signalized traffic circles.

2 TRADITIONAL SIGNALIZED TRAFFIC CIRCLE

2.1 Features of the traditional traffic circle

The traditional signalized traffic circle has the following features:
- legs that connect tangentially, both in the approach and departure directions;
- a large diameter;
- lines that can be spiral-shaped, but without consistent branching according to driving direction.

The tangential connection of the legs on a signalized traffic circle results from the fact that the general traffic flow on the circle was originally based on the weaving of the specific traffic flows on the circle. As soon as these circles were provided with traffic lights, this necessity disappeared. Nevertheless, the tangential form of connection still has its uses on a signalized circle. One positive aspect is the fact that this form creates distance between the departure leg and the approach leg. This distance helps provide positioning room for the traffic turning left, which in turn is necessary for the application of a two-phase control. Another positive aspect is the fact that the angle between conflicting parties is small, which reduces the conflict speed (the resulting conflict speed is about 60% of the vehicle speed). However, the speed at a tangentially connecting approach leg can be high; this higher speed can undo the advantage of the smaller conflict angle.

Another disadvantage of tangentially connecting the approach leg is that the conflict areas are large in comparison with the remaining positioning room, due to the small angle between the roundabout and the connecting legs. To ensure that there is adequate...
positioning room on the circle, the traditional signalized traffic circles were usually designed with a large diameter. An external diameter of 125 m is no exception (see Figure 1). Diameters of 200 m also exist. This is the reason why these traffic circles occupy so much space.

**Figure 1** Two types of Signalized Traffic Circles:  
*left* Roundabout Kooimeer in Alkmaar (a conventional type)  
*and right* Hofplein in Rotterdam (an adjusted type) (Google Maps)

At first, Dutch signalized traffic circles were equipped with concentric lines, called the ‘conventional’ marking in the Dutch Guideline for signing and marking roads 1991 (3), (see the two left pictures in Figure 2). The basis for the arrow markings was not formed by the entire circle, but rather continuously by the next partial intersection. According to these markings, the middle entry lane can be used for turning right, turning left, or driving straight ahead. The left entry lane can be used for both left turns and through traffic, while slightly further ahead the lane is reserved for traffic turning left. The consequence of this marking system is, that many weaving movements are necessary at a short distance and that the outer lane on the circle is not used properly. In practice, the conventional lines caused so many problems that they were increasingly replaced by spiral lines – the second stage in the development. In the third stage, finely, the arrows are based on guiding motorists through the entire traffic circle (4), (the third picture in Figure 2).

**Figure 2** Development in marking of concentric traffic circles
The following comments can be made:

a) The spiral lines are an improvement over the concentric lines. When the circle diameter is approx. 100 m, however, the traffic on the circle underutilizes the left lane, because the drivers on the circle have to change lanes at a short distance in advance of exiting. This limits the capacity for the traffic turning left.

b) To limit the width of the entry points, the two left entry lanes are intended for both turning left and going straight ahead. If left turning traffic is limited, a two phase control is beneficial, as is proved at the Kooimeer roundabout in Alkmaar (Figure 1, left). For this roundabout, a study from 1986 (5) showed that the two-phase control has a capacity that is 23% higher and a cycle time that is 27% shorter than that of a four-phase control. However, if the left turning traffic increases, queues are formed that blocks the traffic flow moving forward on the left through lane, and on the circle the left lane for the left turns is not used properly. In this case four-phase control is necessary.

2.2 Examples of variant solutions

In response to traffic flow problems, traffic circles can also be equipped with lines that make changing lanes unnecessary. For some existing traffic circles, lanes solely intended for flows turning left are already available at the approach. This can result in a significant increase in the capacity of such a circle with a relatively small diameter. An example is the Hofplein in Rotterdam (Figure 1).

The Dutch literature lacks a systematic discussion of the importance of lane markings on the circle in relation to the possibilities and conflicts with traffic signal control. The study of Ma et al. (6) is based on spreading the left-turn traffic over several lanes on the second segment after entering via one lane on the first segment. But that solution holds the disadvantage of the inefficient use of several lanes in a short distance on a traffic circle with a limited diameter.

2.3 Conclusions on traditional traffic circles

In the past, large signalized traffic circles have been built in many different forms, with various modifications over the years. In summary, the weaknesses of the traditional signalized traffic circle are:

- high speeds in the conflict areas;
- the need to change lanes on the circle in order to make good use of the left turn lanes;
- an inefficient use of the space, which is why a large diameter is required.

In practice, these problems sometimes result in these circles being modified by:

- allocating separate lanes for left turns to the entry point;
- assigning lanes exclusively to a single direction (Hofplein in Rotterdam).
It can generally be concluded that the combination of the traffic lights and the necessity of changing lanes between successive decision points makes traffic flow problematic on this type of circle.

3 TURBO CIRCLE DESIGN

3.1 Turbo circle design objective

Given the disadvantages of the traditional signalized traffic circle, an alternative design has been sought which meets three objectives:

a) adequate course guidance;
b) reduction of the approach speed from the approach legs;
c) limiting the required space.

Objective a) leads to the rejection of circle designs with a single central point in favor of a turbo design with (generally) four centers and resulting spiral lanes. Objective b) leads to the radial connection of the approach legs to the circle. Objective c) requires the roundabout segments to provide maximum positioning room for traffic turning left, without hindering the through traffic. On the one hand, this requires the intersection areas to be as small as possible. On the other hand, separate lanes for the different directions need to be available.

In the turbo circle design, these three objectives have been converted into five design features:

1. a geometric design that matches the spiral-shaped tracing (without unnecessary bends) of lanes on the circulating roadway;
2. approach legs that connect radially;
3. departure legs that leave the circle directly after the approach legs;
4. separate lanes in each direction;
5. mountable roadway guide islands (lane dividers) on the circle between lanes leading in different directions, in order to prevent the bend from being cut off at high speed.

These features have been incorporated in steps into various designs. These steps offer a valuable insight into the background of the current turbo circle design.

For the considered signalized turbo circles, pedestrian and bicycle traffic is excluded. Including slow traffic (especially when combined with a substantial amount of right turning fast traffic) would increase the cycle time hugely, so these traffic streams are crossing on a different level.

3.2 First step in turbo circle development

First of all, a design has been made which incorporates the first three design features mentioned above. The fourth design feature was initially not used; instead, the design had three lanes on the circle segments, as was customary according to the Dutch guidelines. The difference with this, however, is that the left turn lane on the circle begins directly across from the connecting leg. Accordingly, the approach leg gets a separate positioning lane for left turns (see Figure 3). Design feature 1 will be realized
by using four translation axes, over which the radial centers are staggered, as is the case with the rotor roundabout. In this design, the lanes shift position to the outside at each quadrant of the circle. The approach legs connect radially while the departure legs bend off of the circle directly afterwards. This is shown in Figure 3. This diagram was first published in a contribution to the 'Verkeerskundige Werkdagen' traffic engineering conference in 2000 (7).

Figure 3 Geometric design of approach and departure legs on a modern signalized traffic circle with choice lanes on the circle (significant chance of blockage)

In this design, changing lanes on the circle is no longer necessary. There are, however, still choice lanes on the circle, on which traffic can choose whether or not to leave the circle. On a roundabout without traffic lights, these lanes, which are used for different directions, offer great benefits - they allow a roundabout to optimally process changing volume patterns. Nevertheless, as noted before, choice lanes have a major disadvantage on a signalized circle: in the place where left turning traffic and through traffic share a lane, cars waiting to turn left at a red light are sure to block the passage of cars that wish to exit the circle. This usually prevents a circle with a small diameter from functioning well. Based on this qualitative analysis of the traffic flow, a quantitative comparison of this design with a four-leg intersection is not further investigated. The fact alone that joint use of a lane by both through traffic and left turning traffic is not a feature of a standard four-leg crossroads, makes generalizations difficult.

3.3 Basic turbo circle design

Given the problems caused by the solution from Figure 3, a turbo circle has been developed that has exclusive lanes for each direction (8). To simplify matters, the basic design features two lanes per direction, see Figure 4. Depending on the volume pattern, the number of lanes per direction can be varied. The features of this design are summarized below:

- The entry point connects radially to the circle in order to decrease speed and limit the size of the surface area of the intersection. To ensure the speed reduction for radial entries, shields at eye level are vital to indicate from a great distance that also for through going traffic a turning maneuver is necessary.

- The through and left turn lanes are intended exclusively for these directions, as a result of which the feasible queuing length on the circle for left turning traffic is twice as great as it would be with a combination of these directions.
- The lanes for the different directions on the circle are separated by mountable lane dividers which are 30 cm wide. They are already introduced at the entry points. These mountable lane dividers are meant to improve course guidance on the circle and prevent bends from being cut-off, thus helping moderate speed during low traffic periods (as indicated by the radii of the pass through curves).
- The curve radii are quite narrow; the inner radius of the circle being discussed here is 30 m.
- The width of the roadways gradually decreases. After branching off from the connecting entry point, the width of the inner circle roadway is 10 m. After one segment (a quarter of the circle further) it has become the middle roadway, and its width is decreased to 9 m. One segment further it has decreased to 8 m, and merges into the two-lane exit. These widths have been chosen in order to ensure that two truck combinations next to each other have sufficient room to drive on the circle.
- The lanes on the circle have been traced in such a way that the curve radius after the entry curve only increases (and does not alternate between increasing and decreasing). To this end, staggered central points are used in the circle design.
- On the side of the roundabout center, the bend width has been expanded outwards (a bend in the direction of the circle's center) in order to provide the leftmost truck with the opportunity to maintain enough distance from a (large) adjacent vehicle when entering the circle.
- The driving side of the edge markings lies 45 cm from the roadway edge or the guide strip (lane divider).

**Figure 4** Turbo circle (signalized and with exclusive lanes for each direction)

### 3.4 Through-going speed of passenger cars

The through-going speed of passenger cars driving straight on a circle is determined by the bend of the driving curve. This bend depends on three factors:

- the inner radius of the circle;
- the roadway width;
The required positioning length determines the diameter of a turbo circle. The road serviceability for trucks determines the lane widths. The through-going speed can only be limited by the position of the approach leg with respect to the circle; the further to the left, the greater the angular rotation and the smaller the through-going speed becomes. There are limits to how far the approach leg can be shifted to the left, however. If it shifts too far to the left, there is another danger - the direction of the course, left or right, becomes unclear. When both matters were weighed up, the choice was made to position the approach legs in such a way that the extended part of the left 'road side' of the through lane runs through the central point of the circle.

4 TURBO CIRCLES WITH WIDE GUIDE ISLANDS

4.1 Marking problems on a compact turbo circle

When a circle is constructed according to the description in paragraph 3.3, the course guidance for the through-going movement at the approach to the circle is provided solely by the markings. However, line markings are inadequate for this purpose (see inset Figure 4). This course guidance can only be correctly provided with the help of robust road surface LEDs. However, these were not available when the first turbo circles were being constructed. In order to eliminate the risk of maneuver errors at the approach to the circle, an alternative solution has been found: mountable traffic islands on the circle. See Figure 5.

4.2 Mountable guide islands

There are two reasons why a mountable guide island is preferable to a non-mountable solution:

- a non-mountable guide island must be marked by a sign, which itself increases the risk of collision;
- a mountable, elevated guide island always allows a driver to rectify an initially wrong lane choice at a low speed, or to deal with an error made by a fellow road user. In terms of Sustainable Safety, this is also called the 'forgiving' aspect of a solution (9).

The most important aim of the guide islands is to provide better guidance. They do have a disadvantage, however: they make it more difficult to gain a clear overview of the circle. This is especially true for passenger car drivers; truck drivers have a much better overview (10). Due to the multiple functions of the traffic islands (providing guidance, functioning as an 'error correction zone' and providing space for the Traffic Control Installation masts), the first part (aligned with the driving direction) must be mountable, 7 cm high and bordered by a rumble strip. This is lower than the guide islands on the turbo circles already constructed, and results in an improved overview of the circle. In the approach direction, the traffic island must be bordered by a higher strip (11 cm),
because that part of the island should draw attention to an obstacle. A traffic sign can then be placed on that part at the level of the stop lines on the entry point. That high part must quickly slope down to 7 cm, because a high traffic island limits the ability of passenger car drivers to gain an overview of the situation. A black and white pillar can be used as an obstacle sign at the level of the stop lines on the circle, as well as on the branching point between the circle and the branching leg (as long as there are obstacles up head).

Figure 5  Turbo circle with traffic islands (number of lanes for turning right and left varies per entry)

5 COMPARISON WITH OTHER CROSSROADS SOLUTIONS

5.1 Aspects for consideration

In order to make an informed choice of a traffic solution in the form of a turbo circle, other possible crossroads solutions need to be considered. The following aspects play a role in such a comparison:

a) traffic flow in terms of capacity and loss time;
b) safety;
c) use of space;
d) investment and maintenance costs;
e) environmental aspects (noise and emission).

In order to compare these aspects, which are basically incomparable, an economic estimation can be of use. For aspects a) to d), widely accepted methods for determining a macroeconomic cost-effectiveness ratio are available. In the case of the environmental aspect, the matter is more complicated, both with regard to the economic estimation of
it, and to the specific environmental factors that play a role. This article will restrict itself to the two aspects mentioned first.

5.2 Traffic flow

Below, the traffic performance of a turbo circle is compared to that of a signalized crossroads (11). The same number of lanes was used for both the four-leg crossroads and the turbo circle, namely two for each direction. Traffic movements are labeled as shown in Figure 6. The moment the cycle length reaches the limit of 120 seconds has been defined as a capacity indicative of the four-leg crossroads. In principle, this also applies to the turbo circle, but with an increasing amount of traffic turning left, the positioning length on the circle is the deciding factor for a shorter cycle length and therefore also for the capacity.

For reasons of clarity, the intensities of all directions have been made dependent on the through-going direction of the leg with the highest volume, in direction 02, by means of four factors:

- factor (a) ratio of direction 08 and direction 02;
- factor (b) ratio of direction 05/11 and 02 (the side directions evidently have an equal volume);
- factor (c) ratio of right turn and through-going – this applies to each approach leg;
- factor (d) ratio of left turn and through-going – this applies to each approach leg.

As expected, factor c) 'right turn and through-going' has little influence on the capacity comparison. On the other hand, factor d) is a strong determining factor for both the functioning of a four-leg crossroads and that of a turbo circle. Eight variants, represented by the letters A to H, were chosen for the combination of factors (a) and (b), while factor (d) varies from 0.2 to 2. In the calculation process, the volumes have been increased in steps until the criteria for the maximum cycle length (120 s) has been reached or until the positioning room on the circle has been filled up. In this way, 80
variants have been calculated (see (2), Appendix G.4). Capacity calculations follow an analytical model, described (11).

Figure 7 shows the development of the total capacity and that of the main flow for a single combination of the factors a) and b) while varying the ratio of left turn and through-going (for both the four-leg crossroads and the turbo circle. The cycle length that elapses when traffic increases is shown for the same variant with an equal amount of left turning and through traffic (Figure 7, above right).

Based on these calculations, three conclusions can be drawn:

- As long as the amount of left turning traffic is smaller than 130% of the through traffic, the capacity of the turbo circle with a diameter of approx. 100 m is greater than that of a four-leg crossroads in all cases. In the volume combination shown, this is applicable as long as the factor d) ‘left turn versus through-going’ is smaller than 1.6. In the case of an evenly balanced volume pattern, however, that turning point only occurs when the amount of left turning traffic is twice as large.

- The cycle length, at which a higher capacity is achieved on a turbo circle, is always shorter than that of the four-leg crossroads. As the ratio of left turning traffic approaches the above-mentioned limit, the gain in cycle length increases. In the example of Figure 7, the capacity of the approx. 8800 pcu/h on the turbo circle is reached at a cycle length of 66 seconds, while at a cycle length of 120 seconds the capacity of the four-leg crossroads is approx. 7300 pcu/h.

- The cycle length of a circle is especially favorable in the case of high volumes. In the graph of Figure 7, a circle with a volume lower than approx. 5500 pcu/h does
yield a gain in cycle length, but the difference is minimal. The gain in cycle length
of a circle is only substantial in the area above 5500 pcu/h (factor > 2).

It must be noted, that in this analytical model the stochastic character of arrival patterns,
as well as the efficiency loss due to green time extension at sub-saturated flow, are
ignored. In reality the capacity will often be lower than determined in the analytical
model.

In the TNO study titled *Evaluatie geregelde turbopleinen* (10), traffic flow is also
discussed. The turbo circle is compared to a four-leg intersection, which is somewhat
similar to the Doenkadeplein in terms of traffic volumes and lane arrangement. It has
been determined that the cycle time on the turbo circle is 40-45 seconds shorter (–47%),
the average waiting time is 7 seconds shorter (–41%) and the maximum queue on the
circle is shorter by 6 vehicles (–39%). These findings correspond well to a difference in
cycle time, which can be greater than a factor 2 in the case of high volumes.

6 TURBO CIRCLE AND TRAFFIC SAFETY

The accidents in the before and after periods of only a single turbo circle, the
Doenkadeplein in Rotterdam (see Figure 8), can be compared. In the before situation,
this was a T-connection of the N471 onto the N209, regulated by traffic lights. After the
lengthening of the N471, it became a turbo circle with four connecting
legs.

**Figure 8**  *Doenkadeplein; Turbo Circle with Overhead Signs*

Despite the addition of a leg (and the increase in the amount of traffic), the number of
registered accidents per year is smaller after the construction of the turbo circle: in six
year before-period 2.67 per year and in three year after-period 2 per year (level of significance 55%). The pattern has also been distinguished according to the seriousness of the accident, in accordance with expectations: accidents with injuries in the before-period 0.83 per year and in the after period 0.33 per year (level of significance 39%); serious accidents: in the before-period 0.33 per year and in the after period 0.00 per year (level of significance 32%). Due to the low figures, however, the differences are not significant, which means that no hard conclusions can be drawn about the safety of the turbo circle.

For the sake of completeness, the accidents on the Tolhekplein have also been taken into account. No figures exist for the prior situation, while the intensity is 62% of the intensity on the Doenkadeplein. For this reason, these accidents have been multiplied by a factor of 1.6 in order to include them as an imaginary extension to the after period of the Doenkadeplein. This leads to the conclusion that the number of serious accidents decreases with a reliability level of 68% due to the construction of a turbo circle (not significant; in seven years of observation, not a single accident resulting in serious injury has been recorded).

Outside the Netherlands the safety of the mountable raised lane dividers may be questioned. It may be clear, that registered accidents on 16 spot-years do not indicate that mountable raised lane dividers will have a negative effect on safety. Even more, a large reduction of accidents associated with injury is observed for turbo roundabouts (12).

In any case, these figures do not indicate that a turbo circle is unsafe, as behavioral scientists expected it would be on the basis of recorded maneuver errors (10). It seems that by labelling 'maneuver errors' as 'unsafe behavior', behavioral scientists – considering the suggestion that this poses with regard to the level of safety of a traffic solution, expressed in numbers of accident victims – have not fully taken into account the speed of the potential conflict partners. The recommendation to be 'cautious in the application of this type of intersection' is not supported by the figures. A higher score in a perception survey does not guarantee greater safety.

7 CONCLUSIONS AND DISCUSSION

In this article, the possibilities of combining traffic lights with roundabouts and/or circles have been studied. It can generally be concluded that traffic lights are only useful on entry points with more than one lane. Even on two-lane roundabouts with a small diameter, however, a complete traffic control barely improves the capacity. There are possibilities for substantially improving the traffic flow with the help of roundabout metering lights.

On circles with more than two lanes, traffic lights are required for satisfactory traffic flow. Historical research has shown that two-phase control makes better use of the geometric features of a circle for smooth traffic flow than four-phase control.
Two-phase control requires sufficient positioning room for traffic turning left. The traditional traffic circles with tangential connecting approach and departure legs are inadequate for two reasons: the intersection areas require a relatively large area, so that not much positioning room remains, while a traffic flow turning left often blocks the through traffic due to the lane arrangement on the circle. As an alternative to this, the first author designed the turbo circle, which features the following elements:

- approach legs connect radially;
- departure legs leave the circle tangentially directly following the approach legs;
- lanes are movement specific.

A critical success factor for the use of the turbo circle is the degree to which drivers are able to choose the correct lane on approaching the circle. Guide signs on overhead gantries, which feature arrows based on the roundabout symbol, provide adequate information for this purpose (see Figure 8; in the picture the second overhead sign is placed accordance the Dutch Guideline for Directional Signing; the first overhead directional sign has to be placed at the start of the pre-sort section, introduced by a pre-directional sign on the road stretch before).

The turbo circle's advantage in terms of traffic flow – short cycle lengths which result in short queues – is a disadvantage in terms of ease of use; the positioning areas can be too small to provide room for the two consecutive gantries with signs, which are needed to provide a sufficiently clear traffic situation.

In order to prepare drivers in advance for the selection of the correct auxiliary lane before they actually reach the lane selection areas, a new advance direction sign was created. A limited study was conducted in order to test various alternative types for effectiveness. On two-lane approach legs, road arrows (in the form of roundabout arrows), over a length of 180 m before the start of the actual lane selection areas, can aid lane selection.

In comparison with a crossroads with the same number of approach lanes, an improvement of the total capacity by 1500 pcu/h (from 7000 pcu/h to 8500 pcu/h), combined with a reduction of the cycle length from 120 to 60-80 seconds, is an example of expecting performance.

The crash history of turbo circles so far shows a pattern of improved safety. However, due to the small number of observation years, no reliable statement can be made about improved safety based on the decreased number of injury accidents following the construction of a turbo circle.

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