Roundabouts - Application and design

A practical manual

Ministry of Transport, Public Works and Water management
Partners for Roads
June 2009

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EXECUTIVE SUMMARY

The roundabout is a popular solution for traffic intersections nowadays. The number of applications is growing continuously, mainly for reasons of road safety and traffic flow quality. The main advantages of the roundabouts are the following:

- Road safety: the risk of accidents is (very) low. A first reason is the low driving speeds of all traffic approaching the roundabouts and the traffic within the roundabout itself. A second reason is the number of potential conflicts among road users, which is lower than on other types of intersections.
- Traffic flow quality: roundabouts have high levels of service in terms of traffic flow for all road users, compared to a normal priority intersection or an intersection with traffic signals.

Correct application and good design of the roundabout are a prerequisite to achieving the desired effects. This Manual therefore aims to spread the knowledge and broad experience, especially from Western European countries, with respect to the application and design of roundabouts, both for single lane roundabouts and for multi lane roundabouts. The main target group of this ‘practical manual’ is the road designer.

The main principle for achieving higher traffic safety in the Netherlands is the concept of Sustainable Safety, in which a triangular relation between function, use and design of a road is put central. The balance of these three elements must guarantee clarity to the road user and lead to the intended, safe road behaviour.

For choosing the right type of intersection several criteria play a role, of which three are most relevant: the function of the intersection roads, the capacity needed in relation to the traffic volumes and the road safety considerations. Roundabouts typically fit into situations with roads connecting districts to each other and to higher level (national) roads. The type of roundabout (single lane, multi lane, with or without bypasses) is highly dependent on the capacity requirements. This Manual provides guidelines to estimate capacity using formulas and specific software applications.

The main elements of an appropriate design of single lane roundabouts are explained. One of the most important issues related to the safety of roundabouts is entry design. Most countries, including the Netherlands, prefer radially connected legs in order to emphasize the approach of the roundabout and to minimize driving speeds. The presence of splitter islands is recommended. The preferred dimensions of various design elements are provided, to enable the roundabout to function efficiently and safely. Experiences in Western European countries over the last decade show substantial reductions in traffic accidents when applying the correct design guidelines. Uniformity in the design is also an important element to the road user.

For situations in which single lane roundabouts can not cope with the expected traffic volumes, even with the provision of bypasses (physically segregated right turn lanes), multi lane roundabouts might be the solution. The main elements for an appropriate design of such roundabouts are explained, including the number of entry and exit lanes. One of the major safety problems of multi lane roundabouts is the weaving and cut-off incidents that frequently occur, as well as interactions with vulnerable road users, i.e., cyclists and pedestrians. Because of the poor performance of multi lane roundabouts with respect to safety and capacity, they are no longer applied in the Netherlands; instead, they have been replaced by ‘turbo roundabouts’. Turbo roundabouts are multi lane roundabouts with spiral road markings and separated circulating lanes. They perform much better with respect to capacity and safety than standard multi lane roundabouts, while they do not need any additional space.

In this Manual the various types of turbo roundabouts are shown and their design elements explained. Once again, uniformity and clarity in the design is a crucial element to provide a traffic solution that enables the road user to perform the desired, safe traffic behaviour.
For any type of roundabout, there are some special road users that require specific attention in the roundabout design: pedestrians, cyclists, public transport vehicles, emergency vehicles and extra large vehicles.

A short section at the end of this Manual covers signalized roundabouts, roundabouts that use traffic signals to arrange the traffic flow efficiently and safely.

Single lane roundabout

1 INTRODUCTION

1.1 Need for a manual

Roundabouts are intersections with a one-way circulating carriageway around a central island. Vehicles on the one-way circulating carriageway have priority over those approaching the roundabout. The roundabout as a solution for traffic intersections has broad interest in many countries nowadays, mainly for reasons of road safety and traffic flow quality. Especially in Western Europe much knowledge and broad experience is available with respect to the application and design of roundabouts, both for single lane and multi lane roundabouts. The main advantages of 'western' roundabouts are the following:

- Road safety: the risk of accidents is (very) low. A first reason is the low driving speeds of all traffic approaching the roundabout and the traffic within the roundabout itself. A second reason is the number of potential conflicts among road users, which is much lower than in other types of intersections.
- Traffic flow quality: roundabouts have high levels of service in terms of traffic flow for all road users, compared to a normal priority intersection or an intersection with traffic signals.

Within the framework of the Dutch Ministry of Transport and Water Management program 'Partners for Roads', training sessions on Safe Roads are organized in more than ten Central and Eastern European countries. In these training sessions, the application and design of (single lane) roundabouts is one the subjects. Several host countries have indicated an interest in applying roundabouts as an effective means of improving its country's road safety record. Exchange of knowledge and experience is desired to make optimum use of this type of intersection in daily practice. A practical manual dealing with when to apply a roundabout and guidelines for their correct (safe) design can help these countries in their development.

This manual has been compiled by the DHV Group and Royal Haskoning. The activities have been overseen by a working group consisting of the following persons[1]:

– Mr. C. A. Verweij (chairman)	Ministry of Transport, Public Works and Water Management
– Mr. J. Boender	CROW
– Mr. J.P.G. Coopmans	DHV Group
– Mr. M.J.M. van der Drift	Ministry of Transport, Public Works and Water Management
– Mr. L.G.H. Fortuijn	Province of Zuid-Holland
– Mr. D.P. Overkamp	DHV Group
– Mr. P. van Vliet	Ministry of Transport, Public Works and Water Management
– Mr. W. van der Wijk	Royal Haskoning

1.2 Partners for Roads

Partners for Roads is a Dutch initiative in the field of road infrastructure dealing with the mutual exchange of know-how, expertise and experience between Central and Eastern European countries and the Netherlands and among themselves.

Economic development is closely related to the increase in (inter)national trade volume. Since there is no trade without transport, transport plays a crucial role. On average, a one percent increase in gross

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[1] The Ministry of Transport, Public Works and Water management acknowledges Mr. P. Furth of Northeastern University in Boston (USA), who did the proofreading of the final draft of the manual. Mr. P. Furth came up with many useful comments and suggestions, which certainly contributed to the comprehensibility of the document.

domestic product (GDP) entails a two percent growth in transport. As markets become more and more volatile, the demand for the most flexible transport mode, i.e. road transport, will grow accordingly. Road infrastructure will have to keep up with this growth, while road safety must be guaranteed.
By sharing mutual knowledge, expertise and experience the Dutch National Road Administration (Rijkswaterstaat) wishes to contribute to economic development to everyone's advantage. Rijkswaterstaat initiated the multinational cooperation program called 'Partners for Roads', focusing on new and candidate members states of the European Union (EU). All new member states as well as candidate member states can participate in this program.

The program's activities are focused on nine topics, called windows. Window 3 is 'Safe Roads'. In this window, knowledge exchange takes place regarding best practices and development of standards for the design of safer roads. Promotion of 'sustainable safety' and application of (Dutch) best practices by means of training and guidelines is offered to improve road safety in partner countries.

1.3 Aim of the manual

The aim of this document is to provide a 'practical manual' for road designers, transport planners and policy makers. The manual's main target group is road designers. This manual must enable them to design roundabouts that comply with the intersection demands in terms of road safety and traffic flow quality. In addition to a 'standard' design, the manual provides an overview given of the chief parameters of roundabout design and their allowed ranges in the design process. Insight into the effects of the design alternatives is also included.

The secondary target groups of the manual are transport planners and policy makers, who must be able to apply basic information regarding the application of roundabouts in their fields of responsibility for this group it may be, for instance, important to make the right considerations when selecting the type of intersection for a certain situation, including the consequences of each option in terms of traffic flow capacity and road safety.

The basis for this manual is existing guidelines developed in the Netherlands. For single lane roundabouts and multi lane roundabouts (including turbo roundabouts), the Dutch institute CROW has developed national guidelines in the last decade. These and other extensive experiences with roundabouts in the Netherlands have been used to compile this manual. Alongside Dutch experiences, experiences from other western European countries are taken into consideration. Countries such as Germany and France and especially the United Kingdom, the cradle of roundabouts, have made important contributions to the development of roundabouts. Where countries have differing opinions or guidelines this manual will indicate this, providing pro's and con's of each option.

For the user, this manual should be a toolbox of the minimum requirements and guidelines for designing 'safe' roundabouts. These requirements must become crystal clear, while flexibility in the application is maintained for countries to make their own choices. This manual assumes right hand driving on carriageways.

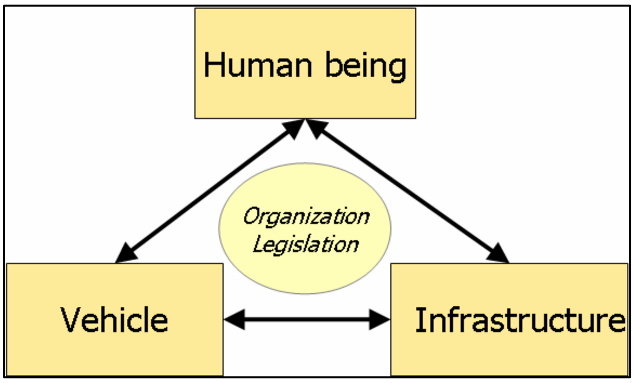
Because the national Roads Administrations are the principal recipients of this manual, the focus in this manual (in line with the Partners for Roads program) is on roundabouts outside built-up areas. Roundabouts inside built-up areas need a (slightly) different approach and have (slightly) different design characteristics.

2 ROAD NETWORK

2.1 Concept of sustainable safety

Road safety is a major concern in many countries. Often the policy on road safety is based on identification and analysis of black spots, giving special attention to vulnerable road users (pedestrians and cyclists) or predominant types of accidents (give way, speeding, alcohol). In countries such as the United Kingdom, Sweden, the Netherlands and Denmark, this policy has proven very successful in reducing the number of accidents and fatalities.

However, in order to continue the downward trend in fatalities and injuries, it has become necessary to develop a more comprehensive approach, based on the interaction between humans, vehicles and infrastructure. In the Netherlands this approach is known as 'Sustainable Safety' [11]. Such approaches have also been developed in other countries, e.g. Sweden's 'Vision Zero' (nobody killed or severely injured in traffic accidents). In the past decade this pro-active approach proved to be effective in bringing about a further improvement in road safety and accident figures. The aim of sustainable safety is to avoid burdening future generations with the consequences of road traffic accidents resulting from current and future mobility demands. Prevention instead of cure is the philosophy of this approach.



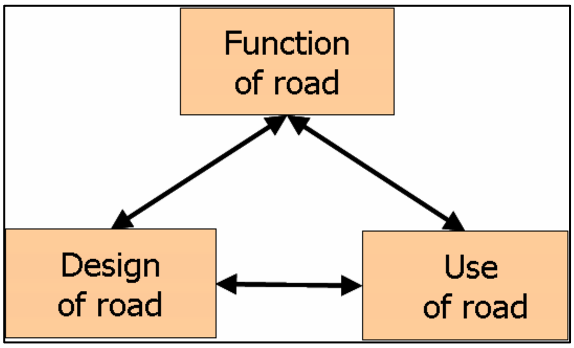
Fundamentally, in a sustainably safe traffic and transport system, smart and safe design of infrastructure limits the chance of an accident to a minimum; and for cases that accidents that still occur, since humans are by definition liable to error, circumstances are such that the chance of serious injury is minimized. Essential in this philosophy is the well-thought infrastructural design of roads and its surroundings.

The concept is based on the principle that 'man is the reference standard' (the human factor will always be present). A sustainably safe traffic system therefore has:
- an *infrastructure* that is adapted to the limitations of human capacity, through proper road design;
- *vehicles* equipped with tools to simplify human tasks and constructed to protect the vulnerable human being as effectively as possible;
- a road *user* who is adequately educated, informed and, where necessary, controlled. The ability and vulnerability of a human being should be the reference standard.

The key to the achievement of a sustainably safe traffic system lies in the systematic and consistent application of safety principles. Road safety should be addressed at all levels.

Safety principles
The starting point for sustainable safety is the human being, with his cognitive and physical limitations as a reference standard. The entire traffic and transport system should be adjusted to the limitations and capabilities of road users. The infrastructure should prevent collisions between moving vehicles with large differences in direction, speed and mass, and should also inform the road user what behaviour is

expected. Sustainable safety is based on a systematic approach in which all elements of road safety and the transport system are geared to one another. At the highest level traffic can be regarded as a system with infrastructure, regulations, vehicles and traffic participants as the main elements.



In order to provide optimum road safety, sustainable safety teaches that three elements must be in harmony: function, design and use (see figure).
- *function:* relates to the use of the infrastructure as intended by the road authority;
- *design*: relates to the physical design and layout properties of the infrastructure;
- *use:* relates to the actual use of the infrastructure and the behaviour of the user.

Each category of road requires a design compatible with its function, while at the same time ensuring optimum safety. To meet the latter requirement, all road categories should comply with the following four main safety principles:
- *Functionality:* preventing unintended use of the infrastructure. Traffic should be distributed over the road network as was intended and the various roads should be used by the types of traffic for which they are designed.
- *Homogeneity:* avoiding significant differences in speed, driving direction and mass of vehicles. Differences in speed and mass between transport modes using the same link or intersection at the same time is reduced to a minimum.
- *Recognizability:* avoiding uncertainty among road users. As much as possible, traffic situations should be predictable. Road users should be able to anticipate the layout of the road correctly.
- *Forgivingness*: allowing for humans to make mistakes by arranging the physical surroundings so that the consequences of mistakes are minimal. Obstacle-free zones are the most important in this respect.

2.2 Road functions

Presently, roads and streets often have more than one traffic function. This does not match with the safety principles as mentioned here. This mix of functions creates unsafe conditions. Multi-functionality leads to contradictory design requirements, and also to higher accident risks. The concept of sustainably safe road transport comes down to the removal of all function combinations by making all roads in principle mono-functional, and by creating clear categories of roads: through roads, collector roads and access roads:
- ***through roads*** primarily have a traffic flow function for long distance traffic, providing rapid and uninterrupted vehicle movement, over a long distance ((inter)national roads);
- ***collector roads*** lead traffic from districts to through roads (and vice versa) and connect adjacent districts to each other (regional roads);
- ***access roads*** provide access to homes, shops and businesses, while also ensuring the safety of the street as a meeting place and a living area, as well as for cyclists and pedestrians (local roads).

Together, these three road categories make up a road network (see figure 2). Road links are intended for traffic flow; intersections are intended to allow traffic to switch from one road to another. An exception is the road link for access roads, on which stopping and turning is allowed. Through roads should not have intersections but split level interchanges to guarantee a continuous flow function.

In addition to a traffic (access) function, access streets and roads in urban areas should allow people to move around the vicinity of their houses safely and comfortably. This residential function can be combined with the access function. A residential function for areas means that pedestrians, playing children, cyclists and parked cars can use the same area. The roads in these areas should be designed in such a way that the residential function is immediately recognizable and prevents driving speeds of more than 30 km/h within urban areas or 60 km/h within rural areas. The possibility of conflicts between non-motorized and motorized traffic may still exist, but the lower speeds on access roads allows good anticipation and avoidance of hazards, and should lessen the consequences of any accident that does occur.

2.3 Recognizable road categories

In a sustainably safe traffic system road users know, for each type of road category, what traffic behaviour is expected of them, and what to expect from other road users. Emphasizing the recognizability of each category increases the predictability. The mechanism that ensures achieving the desired level of predictability consists of two steps:

1. road users must be able to recognize the road category by a (small) number of design elements;
2. based on education and experience, road users should know which possible traffic situations are associated with the road category.

The aim of this mechanism is to lower the workload (or mental load) of drivers. This will have a positive influence on the performance of the driving task.

A small set of design features should ensure the recognizability and predictability of traffic situations (see table 1). Among the most important features are continuous longitudinal road elements Key features are:

- longitudinal road markings;
- separation of driving directions;
- type of pavement;
- presence of vehicle breakdown facility zones (emergency lane on motorways) and obstacle free zones;
- distinct intersection types within a road category.

Table 1: Main characteristics of road categories outside built-up areas

Characteristics	*Through road*	*Collector road*	*Access road*
Speed limit	120 / 100 km/h	80 km/h	60 km/h
Longitudinal edge marking	Continuous	Dotted	None
Cross section	2x1, 2x2 or more	2x2 or 1x2	1x1 (one undivided small lane serving traffic in both directions)
Oncoming traffic	Physical separation	Visual separation	No separation
Emergency facilities	Emergency lane	Semi-hard shoulder	Verge
Obstacle free zone	Large (8 – 13 m)	Medium (4.5 – 6 m)	Narrow (1.5 – 2.5 m)
Slow traffic	Separated	Separated preferably	Mixed, in the carriageway
Intersection	Grade separated	At grade (priority indicated by traffic signs)	At grade

	
Through road, motorway	**Through road, express road**
	
Collector road, dual carriageway	**Collector road, single carriageway**
	
Access road	**Access road, bike lanes**

Figure 1: Examples of categories and types of roads outside built-up areas

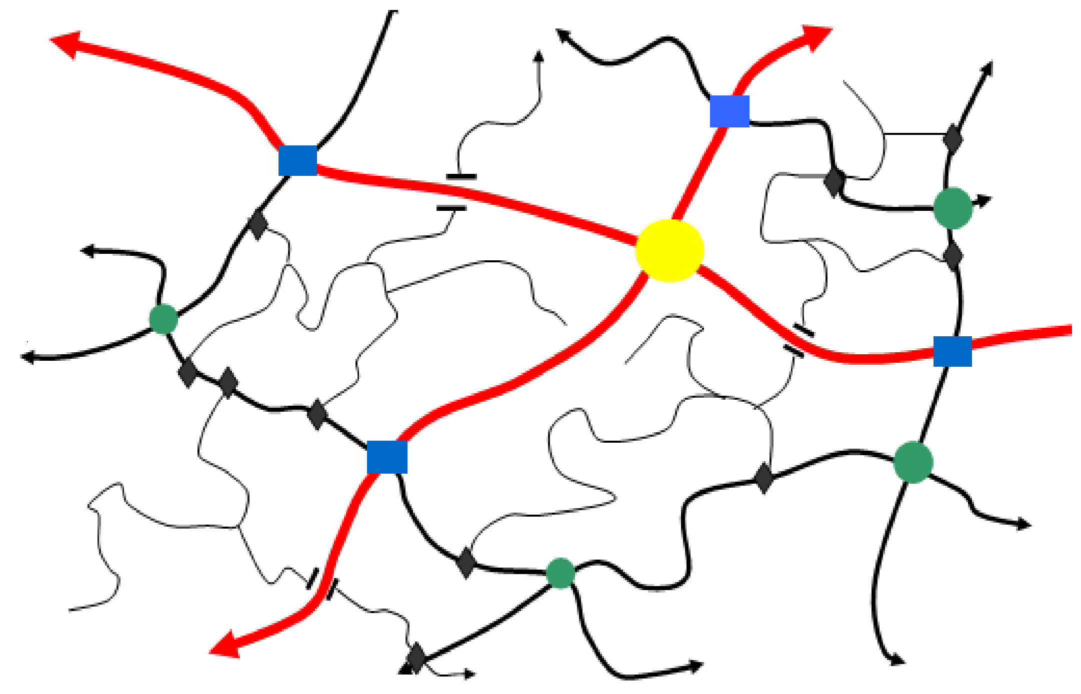
The influence of the design and the environment on driver anticipation is important. As a result on a debate on developing one set of standards, the Dutch road authorities agree on some main (design) guidelines for roads outside built-up areas (see table 1). Figure 1 shows typical pictures of the three road categories.

2.4 Network classification

In almost every country the existing road network is a result of semi-structured developments made in the past. For example, there are many situations in which villages have been united to form one large town, and roads between the villages became part of the urban area of the new town without losing their original function. Such a development can lead to roads whose function, design and use are not in harmony with each other. In practice this is often the case. The challenge for road authorities now is to change this existing road network into a sustainably safe road network, within realistic budget constraints.

When designing new roads and reconstructing existing roads, road safety is one important issue, among many others such as the physical space, the function of the road, the flow capacity, environmental issues and the financial budget. ‘Road categorizing’ should aim to find an optimal balance respecting all of the relevant aspects. In an iterative process, a choice must be made for assigning each road to a road category. This categorization means that every road must be given a specific function. After establishing an overall picture of the network, the choices made for each road can subsequently be translated into practice in transport plans and road designs. It is essential that roads and streets are designed in such a way that they optimally meet the corresponding functional requirements (the concept of ‘self-explanatory’ roads).

A typical (simplified) road network, showing how the three categories of road cover an area and interact, is shown in figure 2. Note that through roads are connected only to other through roads or collector roads, never to access roads.



▬	Through road	⬭	Interchange
━	Collector road	🟦	Grade separated intersection
─	Access road	●	Roundabout (or priority intersection)
		◆	Priority intersection (or roundabout)

Figure 2: Categorization of a road network according to the sustainable safety concept

2.5 Road sections and intersections

The principles of sustainable safety and network classification provide a basis for the design of not only road sections, but of intersections as well (see table 2).

Main or through roads (motorway and express roads) have a flow function. Therefore, both their road sections and their intersections should accommodate fast, long distance traffic flow. Intersections on through roads should preferably be grade separated to promote traffic flow and avoid driving direction conflicts. Wherever two through roads meet, fully grade separated intersections with free flowing sections, called interchanges, should be provided.

Table 2: Purpose of road sections and intersections according to their road categories

Road type	***Road element***	
	Road section	***Intersection***
Through road	Flow	Flow
Collector road	Flow	Exchange
Access road	Exchange	Exchange

Road sections of collector roads are designed primarily for safe traffic flow. Cyclists, and preferably also slow moving motor vehicles (agricultural traffic), should be separated. However, intersections along collector roads do not have a primary flow function; instead, they are primarily meant for the exchange of traffic, allowing changes in driving directions. Within at grade intersections, road users can have driving direction conflicts. For this reason, driving speeds on approach roadways to at grade intersections should not exceed 50 km/h.

On access roads, where traffic modes are not separated, speeds are low and all types of road users share the roadway. Both road sections and intersections of this type of road have an exchange function.

Keeping in mind an intersection’s function in the road network, its type and shape can be determined. There are various options for intersection type, depending on the road category and local circumstances. The next chapter describes the options and the situations in which roundabouts can be good solutions.

3 CONSIDERATIONS REGARDING TYPE OF INTERSECTION

3.1 General introduction

Intersections are potential danger points in the road network. In the Netherlands, more than half the accidents on single carriageway roads occur in at grade intersections. Safety measures at intersections are often more cost effective than safety measures on road sections.
Intersections also determine to a great extent the quality of traffic flow. Average speed along a road depends on the number and type of intersections. Average speed in practice and desired speed according to a road's function in the roadway network should be in harmony.

An intersection has to fulfil a number of general design requirements. It should be:

- *Recognizable*: if a limited number of intersection types are used, with uniform (chief) characteristics, then the road user will recognize the traffic situation more quickly and the situation will comply with expectations.
- *Visible*: an intersection must be visible in time, conspicuous and clearly recognizable and locatable. To see something from a distance, it must have at least a certain size to which the road user's attention and perception can be directed. Contrast, colour, shape and movement are important factors here. Finally, information 'signs' need to be installed in logical, clearly visible places.
- *Surveyable:* when approaching an intersection the road user must be able to oversee the intersection and part of the approaching roads and any traffic on them, in time.
- *Comprehensible*: an intersection is comprehensible to the road user when perceptions of shape, scope, signposting, marking and traffic regulations can be interpreted quickly, correctly and unambiguously on approach.
- *Negotiable*: negotiability of an intersection means that the various design elements fit together sufficiently smoothly. Intersections as well as road sections have to be passable (accommodate the swept path of vehicles). The elements themselves must also be easily passable for the design vehicle.
- *Balanced*: a balanced intersection structure means that the various design elements (including the approach roads) and the traffic measures must form an integrated total.
- *Complete*: an intersection is complete when the traffic at the intersection can continue its way in all possible or intended directions.

In practice several types of intersections are available:

- at grade types of intersection:
  - without right of way signs;
  - with right of way signs (priority intersection);
  - with traffic signals (and right of way signs);
  - single lane and multi lane roundabout;
  - rotary or traffic square with traffic signals;
- grade separated types of intersection, such as:
  - diamond interchange;
  - (half) cloverleaf;
  - split level interchange (flyovers).

The choice of intersection type should be based on a set of several criteria. Obviously each local situation has its own characteristics that need to be taken into account. It is also relevant whether one is referring to a newly built situation or reconstruction of an existing intersection. The most important criteria that always need to be considered to determine the appropriate type of intersection are:

- road category (road function) within the road network;
- needed capacity, considering the forecasted traffic volumes;
- desired level of road safety;
- policy of traffic management;
- spatial possibilities or limitations;
- capital and maintenance costs.

3.2 Road category

In a sustainably safe traffic system, road users know, based on a road's category, what traffic behaviour is expected of them, and what to expect from other road users. A design that emphasizes the recognizability of each category increases predictability (see also section 2.3). The mechanism that ensures the right level of predictability consists of two steps:

- road users must be able to recognize the road category by a small number of design elements;
- based on education and experience, road users should know which traffic situations are associated with the present road category.

The type of intersection contributes to the recognizability of a road's category. As a starting point, the type of intersection that should be applied should be consistent with the road category of the intersecting roads:

- through road : grade separated solutions, priority road (see figure 3);
- collector road : at grade solutions, priority road;
- access road : at grade solutions, traffic from the right has priority.

The main criterion for grade separated solutions is the road category. Motorways have always to be equipped with interchanges. Also, for express roads (speed limit ≥ 90 km/h) with dual carriageways the grade separated interchange is the preferable solution.

Cloverleaf interchange between two crossing motorways

Diamond interchange, connection between a motorway and a collector road

Figure 3: Examples of grade separated intersections

Through roads and collector roads are always priority roads, both inside and outside built-up areas. The choice of intersection type is in principle (see also figures 2 and 4):

- through road – through road : grade separated interchange, for instance cloverleaf;
- through road – collector road : diamond interchange, half cloverleaf;
- collector road – collector road : roundabout (or signalized intersection);
- collector road – access road : priority intersection (or roundabout);
- access road – access road : unsigned intersections, drivers from right have priority.

If two collector roads cross one another at grade and a roundabout is not feasible, the designer has to decide which of the two roads should be the priority road. Points to consider are:

- the differences in hierarchy;
- the differences in traffic volumes;
- a public bus route;
- the traffic flow quality for cyclists and pedestrians.

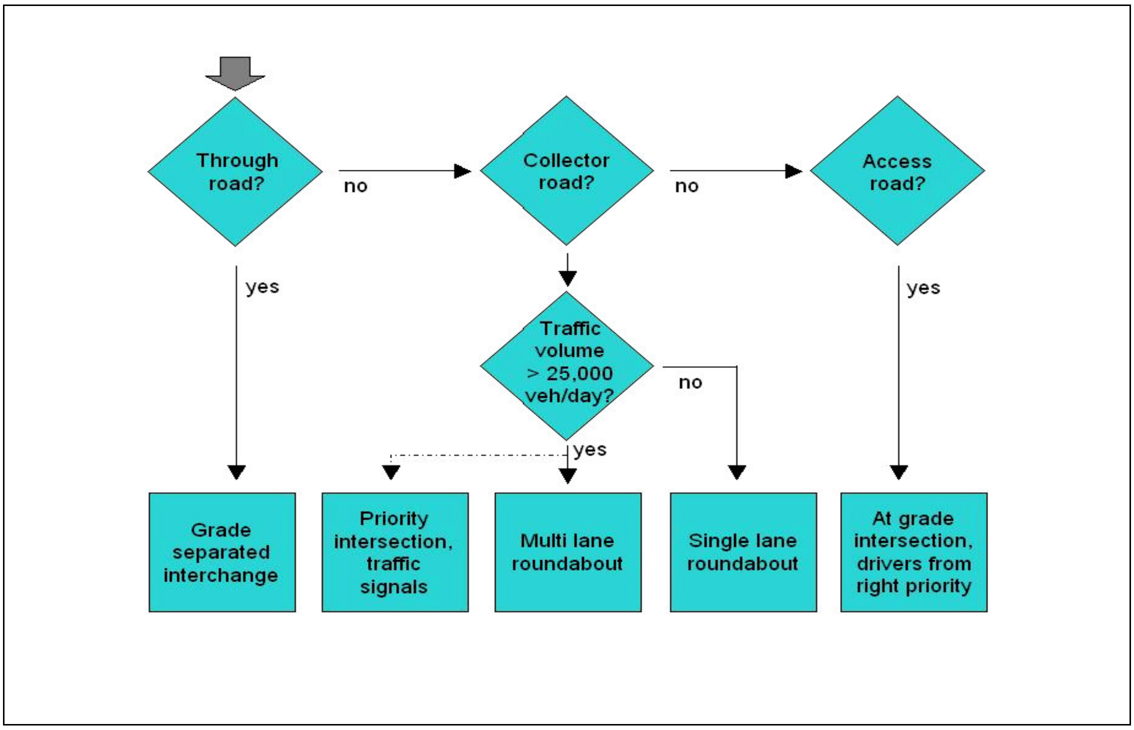


Figure 4: Simplified flow chart choice of intersection

In addition to its function as an intersection, a roundabout may be useful to:

- facilitate a change in road category or road type, for example from dual carriageway to a single carriageway road;
- emphasize the transition from rural to urban environment (border of a built-up area);
- allow U-turns on roads whose cross section has a median and several private accesses;
- on single carriageway roads where overtaking opportunity is limited, a roundabout can be used to provide an overtaking opportunity by constructing a short length of two lanes on the exit.

Other infrastructural considerations to be taken into account are:

- When several roundabouts are planned on the same route, they should be of similar design (route consistency) to the extent that is possible with the traffic volumes;
- Where a proposed roundabout may affect the operation of an adjacent intersection (or vice versa), the interactive effects should be examined. It is preferable to add a leg to a roundabout rather than to maintain or create a secondary intersection in the direct vicinity of the roundabout.
- A road’s speed depends first on the speed limit (which should be according to the road category), the number and type of intersections and the density of traffic (volume / capacity ratio), primarily at intersections. Therefore, considerations of speed and delay should also be taken into account when determining the type of intersection.

3.3 Traffic volumes

After road category, the second criterion for determining intersection type is the desired quality of the traffic flow. These aspects are determined by two sub criteria: the capacity of the intersection and the delay of traffic on the minor road.

	
Raised intersection, traffic from right has priority	**Priority intersection**
	
Single lane roundabout	**Multi lane roundabout**
	
Priority intersection, traffic signals	**Traffic square, traffic signals**

Figure 5: Examples types of intersection

In roundabouts, the traffic on the circulating roadway should always have the right of way [3] [7] [13]. This is not only for reasons of capacity, but also for reasons of road safety, clarity and uniformity. It is the standard in all West European countries. In the past the priority rule was that circulating traffic on the roundabout had to give way to traffic entering the roundabout (priority to traffic on the right). However, experience has shown that when traffic demand is high, this priority rule leads to gridlock the circulating roadway (see figure 6). In an effort to compensate, long weaving sections were desired, leading to flared and tangential entries (see also section 4.3.2). The problem of gridlock in the circulating roadway can be prevented by reversing the priority rule: traffic on the circulating roadway of the roundabout has the right of way. Because of the positive results obtained in many applications, priority for circulating traffic, and therefore give way on entry, has become the standard for the modern roundabout.

Entry priority, gridlock circulating lane (Ghana)

Figure 6: Consequences of priority rules on roundabouts

3.3.1 Intersection Capacity

An intersection's capacity is the maximum number of vehicles that can be processed during a particular period of time, regardless of the delay. The capacity of a priority intersection depends strongly of:

- the traffic volumes per direction on the major and minor road (in peak hour);
- the number of travel lanes on major and minor road;
- the speeds in practice on the major road;
- the composition of traffic.

Well known calculation methods of priority intersections without traffic signals are given in:

- Highway Capacity Manual 2000. Transportation Research Board. Washington, 2000;
- Handbuch für die Bemessung von Strassenverkehrsanlagen. Forschungsgesellschft für Strassen- und Verkehrswesen, Köln, 2001.

Both calculation methods are quite similar. The outcomes of the assessment on the performance of the priority intersection are reserve capacity per direction and the average delay.

The capacity of a priority intersection increases with a greater number of travel lanes on the major and minor road and a median in the major road. But with an increasing number of lanes, road safety deteriorates substantially. When capacity requires more than one lane per direction on the major road, the intersection should be changed to a single or multi lane roundabout or to a signalized intersection. The application of traffic signals can be considered, when:

- the average delay of left turning road users on the major road, or of road users on the minor road, is more than 30 seconds and
- the application of a single or multi lane roundabout is not feasible for reasons of space, capacity or traffic management.

Capacity of a roundabout

As mentioned before, the capacity is the maximum number of vehicles that can be processed during a particular period of time, regardless of the delay. The capacity of a single lane roundabout is greater than that of a priority intersection. A single lane roundabout handles smoothly 25,000 vehicles per day passing through the roundabout [3]. Up to a certain point, roundabout capacity is even higher than that of a signalized intersection (see section 3.3.5). There are various methods available for assessing capacity in order to decide whether a particular roundabout type can be applied.

The capacity of a single lane roundabout with single lane entries and exits can be increased by:

- the application of bypasses if the right turning traffic is substantial;
- a two lane roundabout and single lane entries and exits;
- a two lane roundabout and two lane entries and exits;
- a turbo roundabout.

Single lane roundabout with bypasses ***Two lane roundabout, two lane entry***

Figure 7: Examples of single and two lane roundabout

Turbo roundabout ***Turbo roundabout with two bypasses***

Figure 8: Examples of turbo roundabouts, with design determined by traffic flows

In the United Kingdom and Germany they consider the two lane roundabout as an acceptable solution [7] [13]. In the Netherlands the experience of road safety of two lane roundabouts with two lane entries and exits is rather negative, with a relatively high number of accidents (most of them with property damage only) due to interweaving and people being cut off near exits (see section 5.1.1). For this reason Dutch highway engineers have developed the turbo roundabout [5].

The level of service of a roundabout is determined by how its traffic volumes compare with its processing capacity. There are various methods available for assessing capacity in order to decide whether a single lane roundabout can be applied. An initial test is extremely global. Depending on that test, more in depth methods can be utilized. An in-depth method is only recommended when solutions are unclear. To determine the capacity of the roundabout, the following methods are available:

– rules of thumb;
– calculation rules;
– macroscopic or microscopic simulation models.

Rules of thumb

A roundabout can usually be utilized if the sum of the entering traffic flows is less than [3]:

– single lane roundabout, single lane entries and exits : approximately 25,000 veh/day;
– two lane roundabout, single lane entries and exits : approximately 30,000 veh/day;
– two lane roundabout, two lane entries and exits : approximately 40,000 veh/day.

The values assume that peak hour volume is less than 10% of daily traffic and only apply to situations without cyclists or pedestrians, or where they have no priority or free passage. This rule of thumb ignores differences in traffic volumes at different times of the day, origin and destination relationship and traffic composition. Therefore it is also advisable to check conflict loads, using a calculation method described in the next section.

3.3.2 Conflict load method formulas

A roundabout can be seen as a series of connected T-intersections. The capacity is reached when the volume on one of the entries is greater than or equal to the capacity at the conflict point. The capacity of an entry is seen here as the difference between:

– Ideal entry capacity or maximum conflict load: the maximum number of vehicles that can enter the roundabout in the absence of conflicting traffic. Ideal entry capacity depends on geometry, weather conditions and the distribution of traffic.
– Conflict loss: the reduction in entry capacity due to conflicting traffic.

The relevant conflicts at an entry are shown in figure 9, denoted by the letters A, B and C. A combination of these three traffic volumes determines the so-called ‘conflict load’. Apparently conflicting traffic (C) means traffic turning right just before the entry, and which influences entry capacity because drivers leaving the roundabout often do not indicate their change of direction, so that drivers waiting at the entry wonder they have to give way or can enter the roundabout. This effect can be reduced by constructing a wide splitter island (and a more spacious roundabout). The maximum conflict load is [3]:

– single lane roundabout, single lane entries and exits : 1,500 pcu/h;
– two lane roundabout, single lane entries and exits : 1,800 pcu/h;
– two lane roundabout, two lane entries and exits : 2,100 to 2,400 pcu/h.

The conflict load is expressed in ‘pcu’ (passenger car units). Not only do trucks and buses have larger dimensions, these vehicles also move generally more slowly, which influences capacity. The ‘pcu’ value for trucks and buses is:

– articulated vehicle or bus in the circulating roadway : 2 to 3 pcu;
– articulated vehicle or bus on an entry to the roundabout : 3 to 4 pcu.

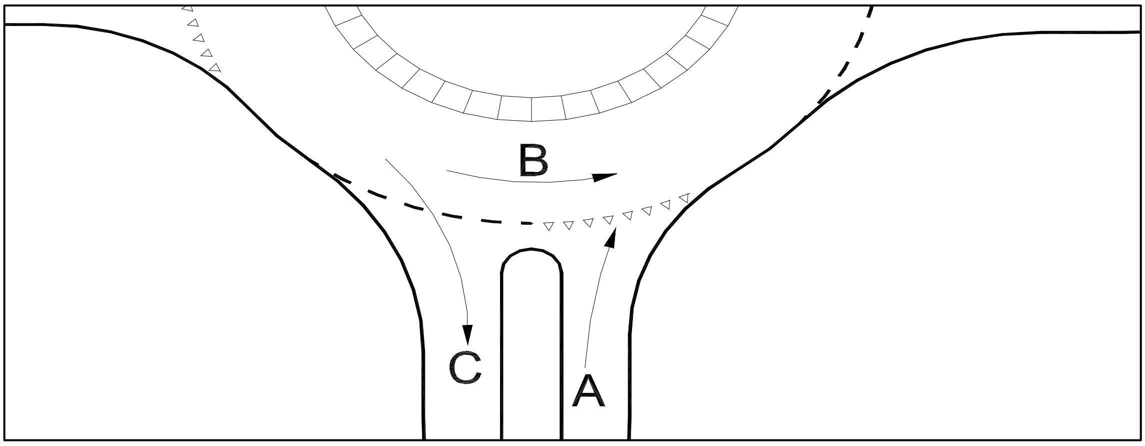


Figure 9: Conflicting flows that determine the capacity of a single lane roundabout

The processing capacity of single lane roundabouts with single lane entries (without cyclists having priority on the roundabout) can be determined using the formula below. Every entry should be tested individually using this formula (see figure 9).

$A_{entry} = 1{,}500 - B_{roundabout} - 0.3 \times C_{exit}$

A_{entry} = entry capacity in pcu/h
1,500 = maximum conflict load
$B_{roundabout}$ = circulating volume in pcu/h
C_{exit} = exit volume in pcu/h

In Germany [18] and Austria a different formula is used, which assumes an average gap in the circulating traffic of 2.7 seconds.

$A_{entry} = 1300 - 0.77B$

Table 3 provides an overview of the capacities of different types of roundabouts and intersections. The table shows theoretical values based on assumed traffic flow ratios main / minor road of 5:2 (for a turbo roundabout) and 3:2 (for spiral and rotor roundabout). In all cases, the ratio of left turning, through and right turning traffic is 1:3:1. (Values calculated using the conflict load method are more specific because they account for the specific traffic flow distribution.).

3.3.3 Nomograms

For other basic types of roundabouts there are no validated methods enabling reliable statements concerning traffic processing capacity. Assessments can best be estimated using the ‘Bovy’ calculation method [3]. This formula (see section 3.3.4) allows one to calculate entry capacity for both single and two lane roundabouts with either single or two lane entries. The method accounts for apparently conflicting traffic on the roundabout turning right just before the entry.

Table 3: **Practical and theoretical capacity of different types of junctions.**

Type of roundabout / intersection	*Capacity in peak hour (± 10% of AADT), all entries combined*		*Conflict load (pcu/h)*
	Practice	*Theoretical*	
Single lane roundabout	2,000	2,700	1,350 to 1,500
Multi lane roundabout with single entry and exit lane	2,200	3,600	1,500 to 1,800
Multi lane roundabout with two entry lanes and single exit lane	3,000	3,600	1,800 to 2,000
Multi lane roundabout with two entry and exit lanes.	3,500	4,000	2,100 to 2,400
Turbo roundabout with two entry and exit lanes (basic design)	3,500	3,800	1,900 to 2,100
Spiral roundabout	4,000	4,300	2,000 to 2,300
Rotor roundabout (three entry lanes and two exit lanes)	4,500	5,000	2,500 to 2,800
Signalized roundabout (3*2 entry lanes)	8,500	11,000	4,200
Priority intersection with left turning lane	1,500	1,800	1,100
Four leg intersection with traffic signals (entries 3*1 travel lanes)	3,500	4,000	3,800
Four leg intersection with traffic signals (entries 3*2 travel lanes)	7,500	8,000	3,800

Using the Bovy formula, nomograms were produced for assessing the capacity of an entry. Figure 10 and figure 11 show nomograms for two types of roundabouts. The following should be noted in respect to the use of these nomograms:

- the nomograms have only been validated to a limited extent;
- two lines are drawn in the nomograms:
  - the upper line shows the maximum flow that can be processed regardless delay;
  - the lower line shows the practical capacity, based on a delay of maximum 20 sec;
- entry volume is plotted on the vertical axis (pcu/h);
- circulating volume is plotted on the horizontal axis, and, in order to account for apparently conflicting traffic, should include a fraction (approx. 30%) of the exiting volume at the same leg;
- if the entry has a bypass, the volume using the bypass is subtracted from the entry volume;
- at roundabouts with cyclists or pedestrians, it is assumed that there is a refuge or splitter island with sufficient space.

Calculations, using the Bovy method, show the following effects when adding a lane at the circulating roadway (two lane roundabout instead of single lane) and at the entries (two lane roundabout):

- A two lane roundabout with single lane entries offers a greater entry capacity than a single lane roundabout with a maximum of 400 pcu/h. Determine whether the single lane exit with a maximum capacity of 1,500 pcu/h can process the volume. The capacity difference decreases proportionately with lower circulating volumes and, ultimately, this difference is nil.
- A two lane roundabout with two lane entries offers a greater entry capacity than a two lane roundabout with single lane entries with a maximum of 800 pcu/h. This difference is reached at extremely low circulating volumes and decreases to approximately 50 pcu/h in the event of high circulating volumes. Here too, determine whether the single lane exits with a maximum practical capacity of 1,500 pcu/h can process the volume.

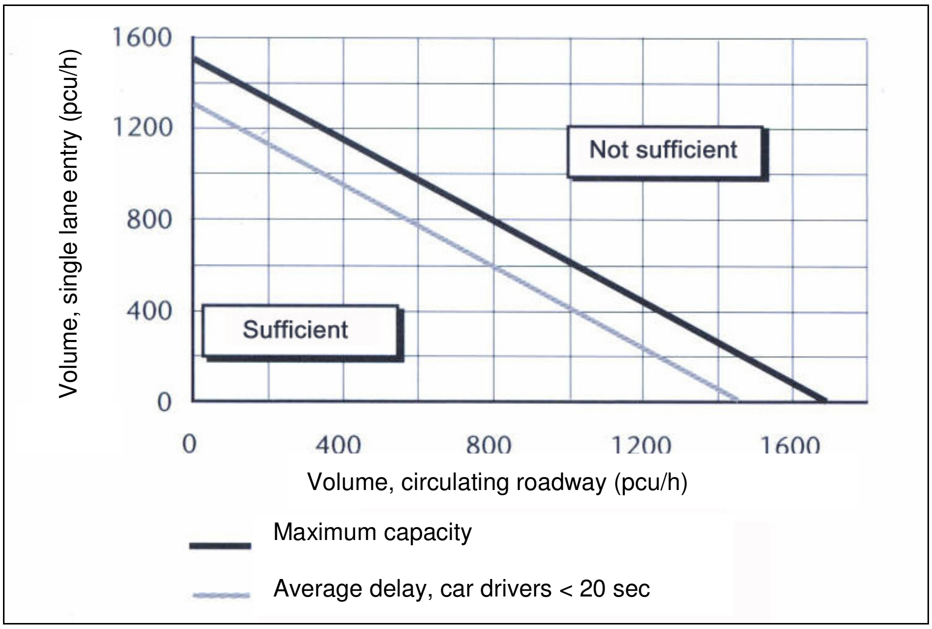


Figure 10: Nomogram capacity of a single lane roundabout with single lane entries (pedestrians and cyclists no priority), Bovy method [3]

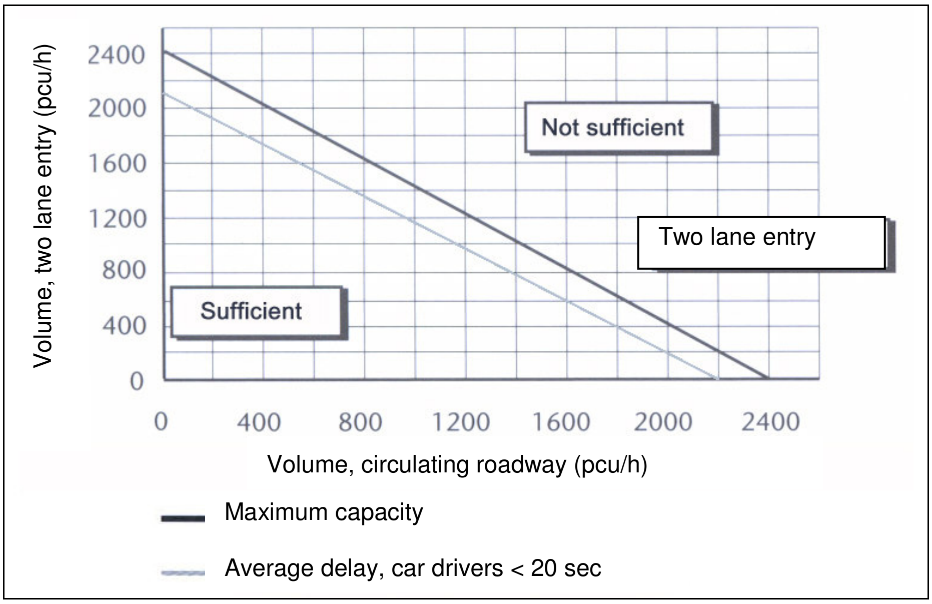


Figure 11: Nomogram capacity of a two lane roundabout with two lane entries (pedestrians and cyclists no priority), Bovy method [3]

For the German method, the basic entry capacity is shown in figure 12 [13]. The German capacities are similar to these in figure 10 for single lane roundabouts. For two lane roundabouts with two lane entries the German basic capacities are much lower than the Dutch recommendations (see figure 11). An explanation is not available.

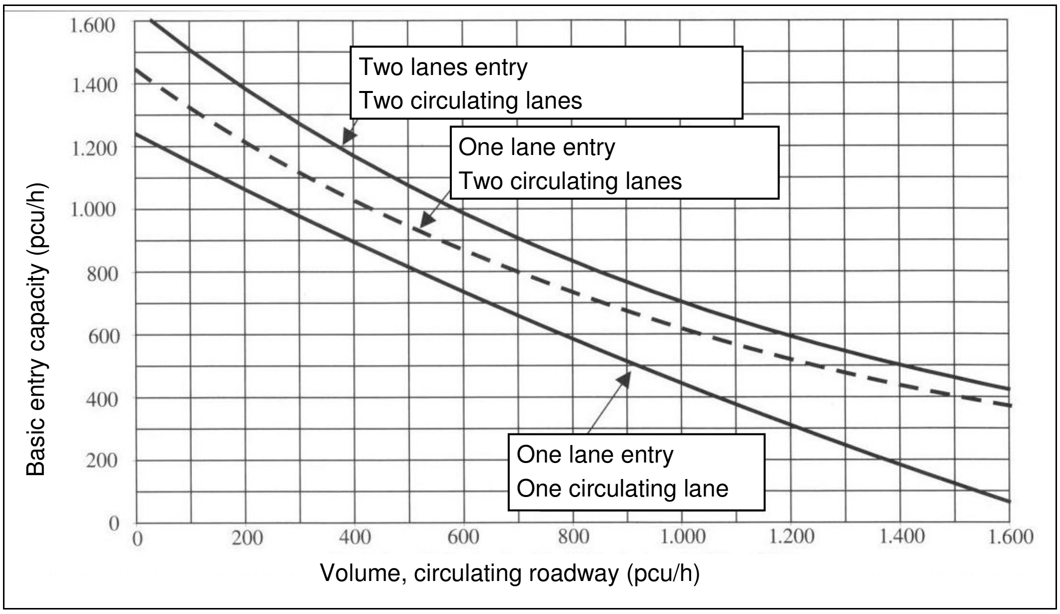


Figure 12: Basic capacity of entries (pedestrians and cyclists no priority) [13]

3.3.4 Multi lane roundabout explorer

Capacity formula based upon theory of gap acceptance

This formula was created in Germany by Brilon and Stuwe based on Siegloch's formula of gap acceptance [1]. This formula is useful for multi lane roundabouts (two circulating lanes) with one or two entry lanes, because there is a minimal follow up time. The formula is:

$$C = 3600.\frac{n_e}{t_F}.e^{\frac{Q_R}{3600}(t_C - \frac{t_F}{2})}$$

C	=	Entry capacity	[pcu/h]
Q_R	=	Traffic flow in the circulating lane(s)	[pcu/h]
t_C	=	Critical gap for the circulating flow (4.3 sec)	[s]
t_F	=	Follow-up time for drivers entering the circulating flow (2.5 sec)	[s]
n_e	=	Parameter for the number of entry lanes:	
	=	1.0 one lane entry	
	=	1.14 two lane entry	

An important feature of the formula is the accounting for the distribution of the traffic flow. However there are some disadvantages:

- drivers may accept a smaller critical gap than assumed;
- apparent conflicts are not taken into account;
- the calculation assumes a standard distribution of the traffic flows. A standard distribution is often less favourable on a multi lane roundabout.

Bovy's capacity formula

In the Swiss formula of Bovy [5] the distance between the entry and the exit determines the influence of exiting traffic on the entering traffic. In the formula a cyclist can be represented by 0.5 pcu and a truck by 2.0 pcu. The formula is:

$$C_E = \frac{1}{\gamma}[1500 - \frac{8}{9}(\beta.Q_C + \alpha.Q_S)]$$

C_0 = ideal entry capacity in the absence of traffic in the circulating roadway (1,500 pcu/h). [pcu/h]
C_E = Entry capacity [pcu/h]
Q_C = volume on circulating roadway [pcu/h]
Q_S = volume exiting on the same leg as the entry [pcu/h]
α = factor reflecting the impact of exiting traffic on entry capacity
β = factor for adjusting circulating flow depending on the number of circulating lanes
γ = factor for adjusting entry capacity depending on the number of circulating lanes

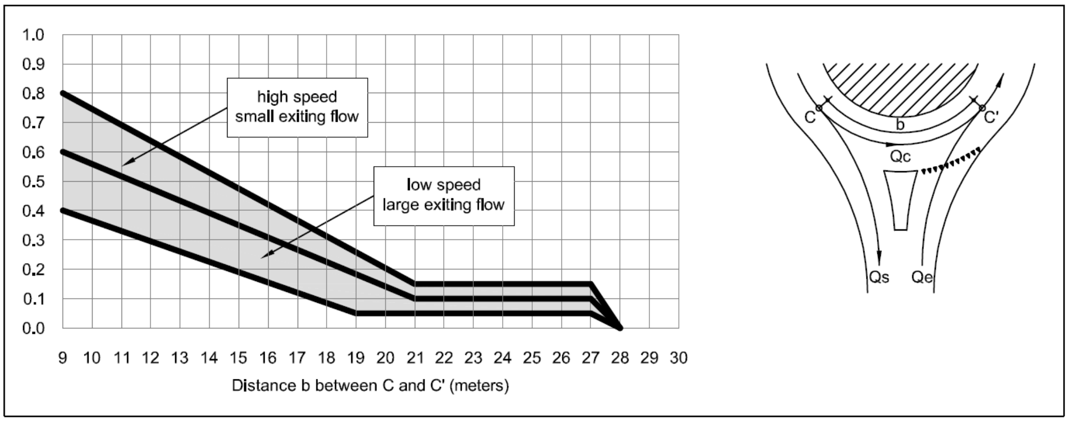
α		
	Single lane roundabouts	Multi lane roundabouts
β	0,9 – 1,0	0,6 – 0,8
γ	1,0	0,6 – 0,7

Figure 13: Parameters in the formula of Bovy [5]

The formulas used in the Dutch multi lane roundabout explorer (see the CD-Rom) are based on the capacity formula of Bovy [5]. The value β has been divided into β_i and β_u for the inner and outer circulating lane of the roundabout, allowing calculations to account separately for each circulating lane . Both values (β_i and β_u) can mathematically be replaced by b_i and b_u. Capacity formulas when there are two entry lanes to a two lane roundabout are as follows.

For the left entry lane:

$$C_{El} = C_{0l} - b_{l,i}.Q_{Ri} - b_{l,u}.Q_{Ru} - a_{l,i}.Q_{Si} - a_{l,u}.Q_{Su}$$

For the right entry lane:

$$C_{E\,r} = C_{0\,r} - b_r\,.Q_{R\,u} - a_{r\,i}.Q_{Si} - a_{r\,u}.Q_{Su}$$

$C_{E\,l}$ = capacity of left entry lane [pcu/h]
$C_{E\,r}$ = capacity of right entry lane [pcu/h]
$C_{0\,r}$ = capacity of left entry lane without traffic on circulating lane [pcu/h]
Q_{Ri} = volume on inner circulating lane (i) [pcu/h]
Q_{Ru} = volume of outer circulating lane (u) [pcu/h]
Q_{Si} = volume of apparent conflict on left exit lane [pcu/h]
Q_{Su} = volume of apparent conflict on right exit lane [pcu/h]
$b_{l,i}$ = factor reflecting how traffic on the inner circulating lane (i) affects the capacity of the left entry lane (l).
$b_{l,u}$ factor reflecting how traffic on the outer circulating lane (u) affects capacity of the left entry lane (l)
$b_{r,u}$ factor reflecting how traffic on the outer circulating lane (i) affects capacity of the right entry lane.
a_{li} factor reflecting how exiting traffic in the left exit lane (i) affects capacity of the left entry lane (l).
a_{ri} factor reflecting how exiting traffic in the left exit lane (i) affects capacity of the right entry lane (r).
a_{lu} factor reflecting how exiting traffic in the right exit lane (i) affects capacity of left entry lane (l).
a_{ru} factor reflecting how exiting traffic in the right exit lane (i) affects capacity of the right entry lane (r).

Table 4: Parameter used in capacity formulas of the multi roundabout explorer

	C_o	b_{max}	b_{min}	$a_{l,i}$		$a_{l,u}$ $a_{r,u}$	$a_{r,i}$	
				splitter island width			*splitter island width*	
				2.5 m	*7 m*		*2.5 m*	*7 m*
Single lane roundabout	1,600	0.85	0.85	0.22	0.16	--	--	--
Turbo roundabout, major flow on left entry lane	1,550	0.82	--	0.21	0.15	0	--	--
Turbo roundabout, major flow on right entry lane	1,550	0.82	--	--	--	0	0.14	0.07
Turbo and spiral roundabout: minor flow, left entry lane (or single entry lane and two circulating lanes.	1,500	0.81	0.68	0.21	0.15	--	--	--
Turbo roundabout: minor flow, right entry lane	1,550	0.82	--	--	--	--	0,14	0.07
Spiral roundabout: minor flow, central entry lane	1,500	0.81	0.68	0.13	0.07	--	--	--
Spiral roundabout: minor flow, right entry lane	1,550	0.82	--	--	--	--	0.06	0
Rotor roundabout: central entry lane	1,500	0.82	0.64	0.13	0.07	--	--	--
Rotor roundabout: right entry lane	1,550	0.82	--	--	--	0	0.06	0

The parameters for turbo roundabouts can slightly deviate in practice. The following passenger cars units were used during the calibration of the parameters:

–	passenger car	: 1 pcu;
–	non articulated truck	: 1.9 pcu;
–	articulated truck	: 2.4 pcu.

3.3.5 Average delay

In figure 14 (main road) and figure 15 (minor road), the average delay for a single lane roundabout is compared with an intersection with traffic signals [21]. This comparison is based on calculations using micro simulation tools. The traffic volume in each direction is assumed symmetrical, while the different number of lanes at the intersection controlled by traffic signals is taken into account:

- TLR 1+1 : traffic signal control, one lane major road, one lane minor road;
- TLR 2+1 : traffic signal control, two lane major road, one lane minor road;
- TLR 2+2 : traffic signal control, two lane major road, two lane minor road;
- TLR 3+3 : traffic signal control, three lane major road, three lane minor road.

The figures show that the average delay of a single lane roundabout is less than the delay for every type of signalized intersection considered. Only after the capacity of the roundabout has been reached does the major road average delay become higher with a roundabout. Therefore it is very important that the traffic capacity of the roundabout is always sufficient to meet the traffic demand.

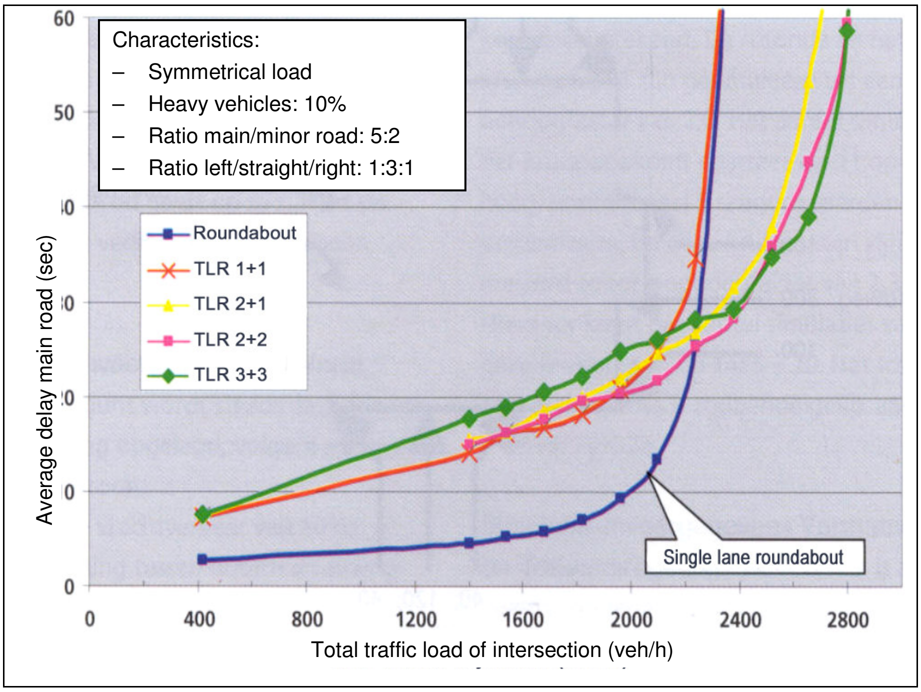


Figure 14: Average delay major road

When operating within their capacity range, roundabouts typically operate with lower vehicle delays than other intersection types and control devices. With a roundabout it is unnecessary for drivers to come to a complete stop. When there are queues on one or more approaches, traffic within the queues usually continues to move. This can only be achieved if the traffic on the circulating roadway of the roundabout has priority.

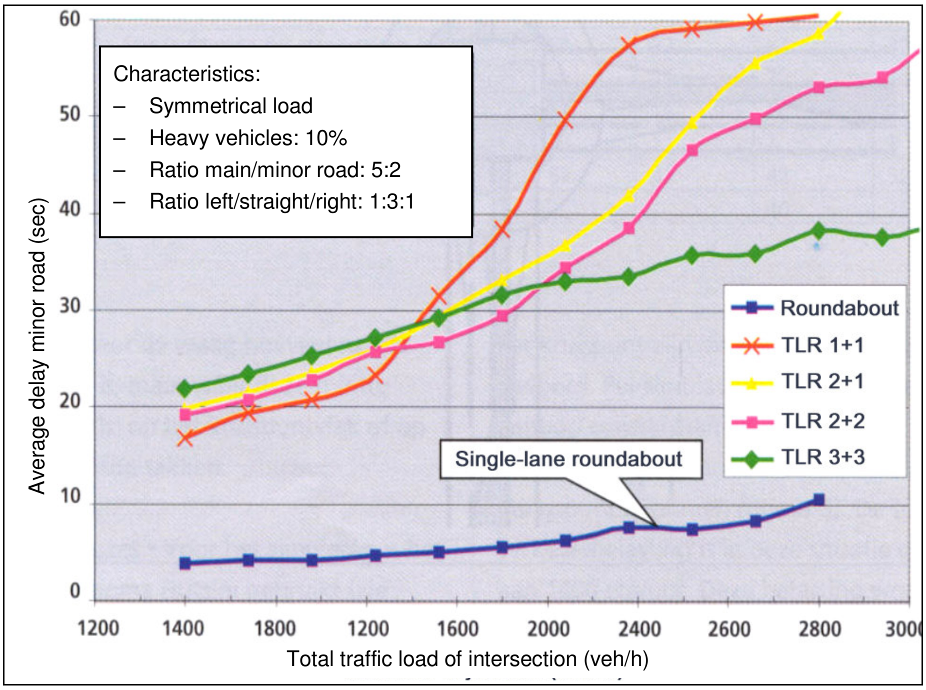


Figure 15: Average delay, minor road

3.4 Road safety

The majority of accidents at priority intersections are associated with left turns from the major or the minor road, and straight through crossings of the major road from the minor road. These types of accidents are eliminated by a roundabout. The roundabout is the safest at grade intersection known. In particular, relatively small single lane roundabouts are safe in general. Dual lane roundabouts are less safe than single lane roundabouts.

Roundabouts both promote the fluid flow of traffic and have an important speed reducing effect. Roundabouts therefore make a substantial contribution to road safety. From the perspective of road safety, capacity, clarity and uniformity, circulating traffic in the roundabout should always have the right of way. The main safety advantages of roundabouts compared to other intersection types are:

- The actual speed of the drivers on the circulating lane(s) and the entry lane(s) is very low. The lower the driving speeds, the lower the risk of (serious) conflicts or (injury) accidents.
- The number of potential conflicts is much lower than with a traditional intersection (see figure 16):
  - four leg roundabout : 8 conflict points;
  - four leg priority intersection : 32 conflict points.
- A roundabout eliminates the most hazardous conflicts. The conflict points on an intersection are not equally serious. There are conflicts of different types: crossing, merging and diverging. Diverging is a minor conflict. A roundabout eliminates crossing conflicts by converting all movements to right turns.
- The roundabout is very well recognizable as intersection by means of the central island, and the conflict points are surveyable.

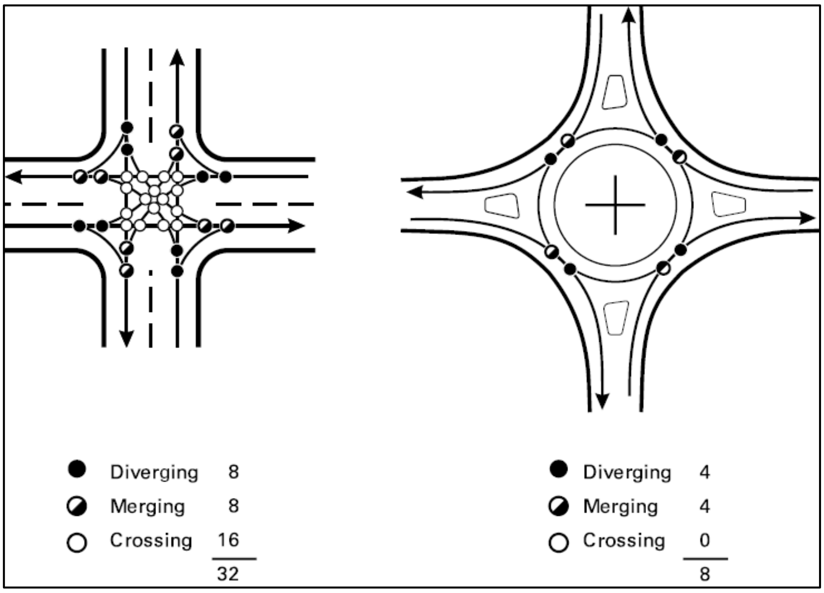
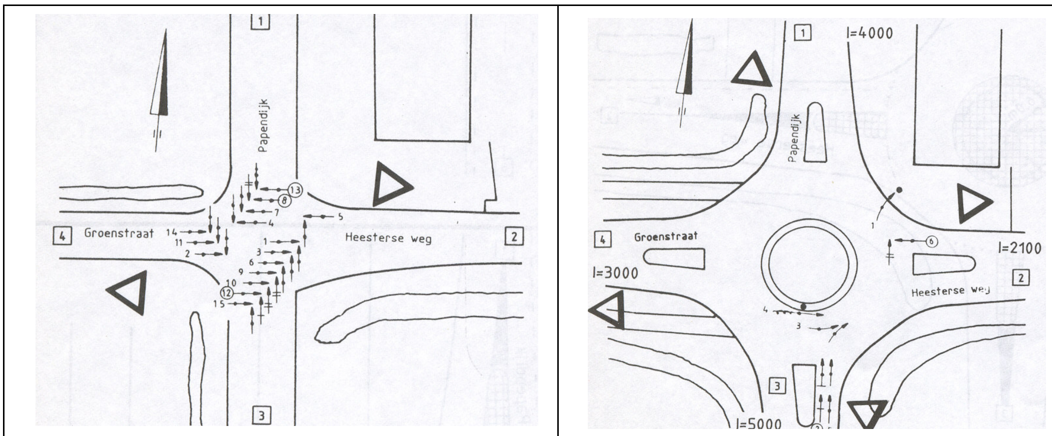


Figure 16: Number of conflict points in four leg roundabout and priority intersections [12]

Several studies have been conducted on the road safety of roundabouts in Europe, especially on single lane roundabouts. In the Netherlands, at locations where priority intersections were converted into roundabouts, the total number of recorded accidents dropped by almost 50% [3] [14]. Outside urban areas, the number of injury accidents decreased by as much as 80%. The positive safety effects of roundabouts also appeared long term. For example, figure 17 shows a strong road safety in a multi-year before-after study of the substitution of a Dutch priority intersection (black spot) to a roundabout.

With two lane roundabouts, the Dutch experience is that the greater accident frequency is not only the consequence of higher levels of traffic, but also because of a substantial number of accidents (most of them property damage only) resulting from interweaving paths and cutting off paths at exits (see section 5.1.1).



Priority intersection, accidents over three years | *Single lane roundabout, accidents over three years*

Figure 17: Roundabout is an effective road safety measure

In the Netherlands (Province of Limburg) the number of injuries per million vehicles passing through different types of intersection has been calculated for different classes of volumes (see table 5). In all cases the roundabout is the safest solution. This good performance appears independent of traffic volumes [30].

Table 5: Injuries rates for different type of intersections [30]

Type of intersection	*V < 10.000 veh/day*	*10.000 < V < 20.000 veh/day*	*V > 20.000 veh/day*
Priority intersection, 3 legs	0.090	0.127	0.127
Priority intersection, 4 legs	0.247	0.127	0.127
Priority intersection, 3 legs, traffic signals	0.113	0.072	0.084
Priority intersection, 4 legs, traffic signals	0.113	0.072	0.102
Roundabout (single lane)	0.080	0.080	0.080

The next set of tables show results from another Dutch evaluation (Province of Zuid-Holland) [14]:

– replacement of priority intersections with single lane roundabouts (see table 6);
– replacement of signalized priority intersections with single lane roundabouts (see table 7);
– replacement of priority intersections with multi lane turbo roundabouts (see table 8).

Table 6: Safety effect, replacing priority intersection with single lane roundabout [14]

Type	*Number (n)*	*Injury accidents/year*	*Accidents/year*
Priority intersection	39	1.24	4.63
Single lane roundabout	39	0.23	2.31
Effect		-82% (significant)	-50% (significant)

Table 7: Safety effects, replacing signalized intersection with single lane roundabout [14]

Type	*Number (n)*	*Injury accidents/year*	*Accidents/year*
Priority intersection, signalized	12	0.72	2.94
Single lane roundabout	12	0,06	2.27
Effect		-92% (significant)	-23% (not significant)

Table 8: Safety effects of substitutions priority intersection by turbo roundabouts [14]

Type	*Number*	*Injury accidents/year*	*Accidents/year*
Priority intersection	7	2.42	11.91
Turbo roundabout	7	0.44	6.06
Effect		-82% (significant)	-49% (significant)

In (almost) all cases the number of injury accidents decreased significantly. The decrease of give way injury accidents is statistically significant; the decrease of rear end accidents is not significant. The results underline the effectiveness of roundabouts. Only when the number of injury accidents per year on a priority intersection is ≤ 0.15, does it seem ineffective to substitute the intersection by a single lane roundabout. Turbo roundabouts do not yield as good a safety improvement as single lane roundabouts; however, they can handle greater levels of traffic.

Research in Germany has also found that roundabouts are safer than signalized intersections; see figure 18 [27]. The accident rate for four leg roundabouts outside built-up areas (0.4 accident / million vehicles) is half compared to four leg intersections with traffic signals (0.8 accident / million vehicles). The related accident costs of roundabouts are about 1/3 of those for signalized intersections.

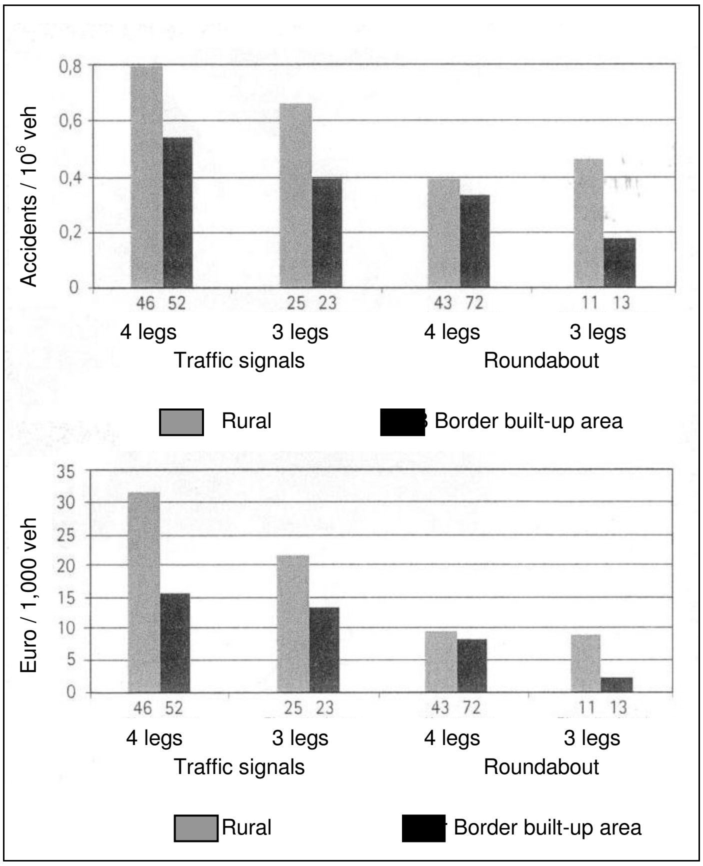


Figure 18: Accident rates of intersections with traffic signals and roundabouts in rural area [27]

In 2004 there were about 207,400 personal injury road accidents in Great Britain [7]. Of these, about 18,000 (8.7%) occurred at roundabouts. The proportion of accidents at roundabouts which were fatal was 0.35%, whereas 0.88% of all other junction accidents and 2.2% of link accidents were fatal. This indicates the effectiveness of roundabouts in reducing accident severity [7]. The average accident cost at a roundabout was calculated to be about 68% of that at other junction types and about 47% of that on links. This suggests that on average, roundabouts are safer than other junction types. However, this will not necessarily be the case for all road users or for a particular junction.

Table 9: Average accident frequency at roundabouts [7]

No. of legs	***No. of sites***	***Accident frequency (accidents/ yr)***			
		single carr.way roads	***dual carr.way roads***	***All roads***	***Accident severity (% fatal and serious)***
3	326	0.63	1.28	0,79	9.3
4	649	1.08	2.65	1.79	7.1
5	157	1.72	3.80	3.66	7.1
6	30	2.11	4.62	5.95	5.2
Total	1,162	1.00	2.60	1.87	7.2

In the United Kingdom a study undertaken in 2004 determined accident frequencies (accidents per year) by severity level over a five year period for a sample of 1.162 roundabouts [7]. The majority of roundabouts are sited in rural areas. The number of accidents per year increases with the number of legs (because of corresponding increases in the number of potential conflict points and traffic flow). On average, there are more accidents at roundabouts with at least one approach that is dual carriageway compared with roundabouts where none of the approaches are dual carriageway, but this can be explained because dual carriageway roads generally have higher levels of traffic.

An accident rate per vehicle could only be calculated for 44 roundabouts which had reliable traffic counts, most of them having high traffic flows. The average accident rate at these roundabouts was 36.2 accidents per million vehicles passing through the intersection.

Table 10 shows the percentage of accidents by mode of transport and by severity of all 1,162 roundabouts sampled [7] in the United Kingdom. The percentage column adds up to more than one since many accidents involve more than one mode of transport:

- Only 3% of accidents involved a pedestrian (note that the majority of roundabouts are situated in rural areas). However, the accident severity for pedestrians is high (vulnerable user).
- Pedal cyclists were involved in about 8% of all accidents, although they typically constitute less than 2% of the traffic flow in the United Kingdom (cyclists are vulnerable road users). The most common accident type is a cyclist on the circulating roadway hit by an entering vehicle.
- Powered two wheelers (e.g. mopeds) are involved in about 14% of the accidents on average, although they are less than 2% of the traffic flow in the United Kingdom. The accident severity (19.3%) for powered two wheelers (vulnerable road users) is much higher than for car occupants.

Table 10: Accidents by mode of transport [7]

Mode of transport	***Percentage of accidents (%)***	***Accident severity (% fatal and serious)***
Pedestrian	2.8	22.6
Pedal cyclist	8.0	9.5
Powered two wheelers	14.4	19.3
Cars and taxis	76.7	6.0
Public service vehicles	2.6	7.8
Light goods vehicles	6.4	5.6
Large goods vehicles	9.3	8.0

In Germany most of the studies calculate an accident cost rate (see Table 11) instead of the accident rate. The accident cost rate calculates the total of the yearly social costs of accidents per 1000 vehicles passing through the intersection.

Table 11 shows the results of two studies [16] [2]. Again, the advantages of roundabouts stand out. The accident cost rate for other at grade intersections is more than 2 to 3 times greater than the rate for roundabouts. Thus, data from Germany confirm that roundabouts have the best road safety of all possible options at grade intersections.

Table 11: Accident cost ratio of type of intersections in rural area

Type of intersection	**Accident cost rate (Euro/1000 veh)**	
	[16]	[2]
Priority intersection	53	66
Priority intersection with traffic signals (2 phases)	54	--
Priority intersection with traffic signals (≥ 3 phases)	27	--
Partly grade separated intersection	27	35
Half cloverleaf	15	--
Intersection with traffic calming	15	--
Roundabout	10	12

3.5 Traffic management

Other criteria that might be included in the considerations for the type of intersection are priority regulations for public transport and traffic flow quality for cyclists and pedestrians. Such issues are based on local situations and prevailing policies.
For public transport on single carriageway roads, the roundabout can be used to provide a bus stop by constructing a short length of two lanes (of which one is a bus lane) on the entry (see also section 4.6.3).

Roundabouts may not be appropriate for use of intelligent traffic systems, integrated traffic management, or other circumstances where access control is required. Roundabouts are mostly not compatible with intelligent traffic systems such as coordinated traffic signals. These systems move vehicles in platoons by adjusting traffic signals. Roundabouts can interfere with platoon movement to the extent that arriving flows at downstream traffic signals are not platooned, and cannot be reliably predicted.

3.6 Space and costs

Roundabouts usually require more space than the rectangular space inside traditional priority intersections. Therefore roundabouts often have an impact on the properties on the corners of an intersection. The total space requirements of a traditional intersection include not only this rectangular area, but also the space needed for the approaching roads. Therefore, if a (signalized) intersection requires long or multiple turning lanes to provide sufficient capacity or storage, a roundabout with similar capacity may require less space on the approaches and therefore less space in total.

Compared to signalized intersections, a roundabout does not have traffic signal equipment that requires constant power, maintenance and regular updating of settings. The life span of traffic signals is typically 15 years at maximum. Roundabouts have very low maintenance costs, and their life span is more than 30 years. If investment and maintenance costs are summarized over 30 years, the costs of a roundabout in most circumstances turn out to be less.

4 DESIGN OF A SINGLE LANE ROUNDABOUT

4.1 General principles

The principal objective of roundabout design is to limit delay for vehicles while maintaining safe passage for all road users through the intersection. Roundabouts should be designed to facilitate the forecasted traffic demand. They work most efficiently when traffic flows are reasonably balanced among legs, but they may also be the optimum choice in other cases. Entry width and the angle between entries and the circulating roadway are the most important determinants of capacity and road safety. Entry deflection is the most important factor for road safety, because it governs the speed of vehicles through the roundabout. Associated traffic signs and road markings can significantly contribute to the safety and the capacity of a roundabout. The need for and layout of these traffic signs and road markings is an integral part of the design process.

This chapter covers the design elements and considerations for single lane roundabouts. The next chapter will discuss the multi lane roundabouts.

4.2 Design principles

Many road safety aspects play a role in the design of the roundabout. Important aspects are speed, uniformity, conspicuousness, visibility and recognizability:

- Road users must be informed that they are approaching a roundabout with plenty of time. Consistent signposting and road markings can contribute to this. Advance signposting, on which the roundabout is recognizably displayed, is a clear signal that one is approaching a roundabout (see section 4.7.2);
- To improve the conspicuousness of the roundabout, it is advisable to raise the central island. It is not necessary for approaching drivers to see oncoming traffic over the central island. However, the diameter of the elevated part must be substantially smaller than the entire central island, in order to ensure visibility of traffic on the entry lanes. The height should be a minimum of 1.10 m (eye level of driver). The design of the island should be collision friendly.
- The entries should be connected radially, creating a near 90 degree deflection on entry that limit entering speeds and supports the priority rule of giving way on entry. For the same reason, entry and exit radii should be as small as possible (see section 4.3).

In a rural area, a roundabout can have three to six legs. It is always good to consider first whether certain connections are really necessary in the road network (see chapter 2). But if necessary, it is preferable to add a leg to the roundabout rather than maintain or create a secondary intersection nearby. A regular spacing of the legs around the circulating carriageway is preferable (this is however not crucial). A well designed distribution of the legs can considerably improve the facility’s comprehensibility.

4.3 Entry design

4.3.1 Radial connected legs

As mentioned in the previous section, the design of the entry is very important for road safety and capacity. Achieving appropriate vehicular speeds through the roundabout is the most critical design objective. A well designed roundabout reduces the relative speeds between conflicting traffic flows by requiring vehicles to negotiate the roundabout along a curved path (deflection). In general, the roundabout is optimally located when the axis lines of all approaches pass through the centre of the central island (see figure 19). This alignment will achieve optimal deflection at the entries and the exits. This design usually allows the geometry to be adequately designed so that vehicles will maintain slow speeds through both the entries and exits. The radial alignment also makes the central island more conspicuous to approaching drivers.

If it is not possible to align the axis of the legs through the centre, a slight offset to the left (so the axis line will pass to the left of the centre) is acceptable. This alignment will still allow sufficient deflection to be achieved at the entry, which is of high importance. In some cases (especially when the inner circle of the roundabout is relatively small), it may be beneficial to introduce a slight offset of the approaches to the left in order to enhance the entry deflection. However, care must be taken to ensure that such an approach offset does not produce an excessively tangential exit. It is important that the exit geometry produce a sufficiently curved exit path in order to keep vehicle speeds low and reduce the risk for pedestrians and / or cyclists crossing the road.

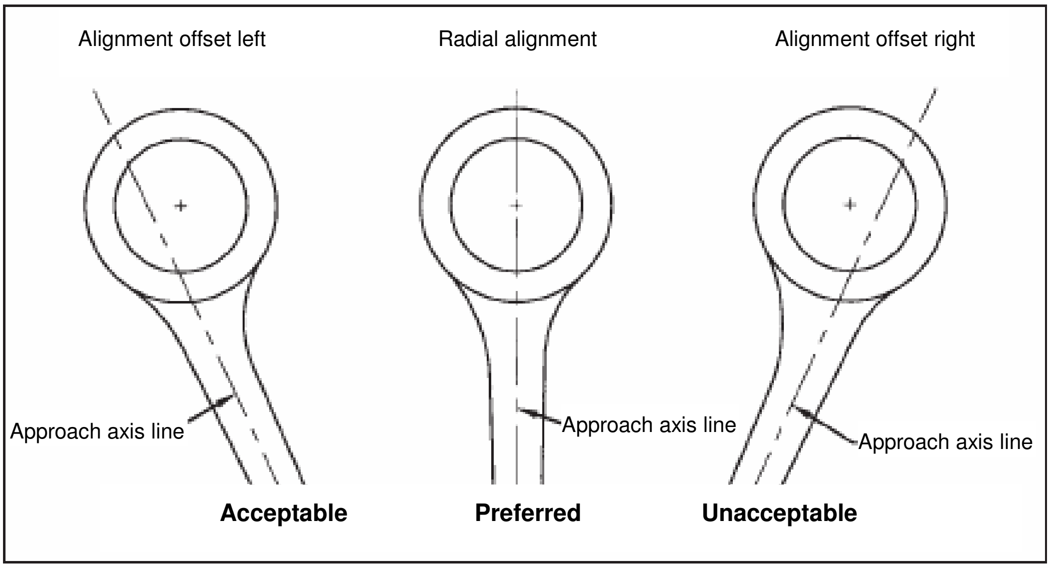


Figure 19: Position of approach axis line in relation to the centre [12]

It is almost never acceptable for an entry alignment to have an offset to the right of the roundabout's centre. This alignment brings the entry in at a more tangential angle and reduces the opportunity to provide sufficient entry deflection. Vehicles will be able to enter the roundabout too fast, resulting in more loss-of-control crashes and higher crash rates between entering and circulating vehicles. Such an alignment also results in a sharp angle between entering and circulating vehicles (< 90°), making it difficult for the drivers on the entry lane to see conflicting traffic on the circulating roadway. Moreover, it is desirable to keep the space between all legs of the roundabouts more or less equal, in order to provide optimal separation between successive entries and exits. This results in optimal angles of 90° for four-leg roundabouts.

When an entry alignment has an offset to the left of the roundabout's centre, vehicles will be able to leave the roundabout at higher speeds. This solution is only acceptable when there are no crossing cyclists or pedestrians. As a general rule, zebra crossings should not be used where the 85th percentile speed exceeds 50 km/h.

Figure 20 shows a Dutch example of an old large roundabout (diameter about 135 m) with tangential connected entries and exits, and priority given on entry (i.e., priority to drivers on the right)(left aerial picture). This roundabout was black spot number one in the city of Amersfoort. In the year 2006 the roundabout was reconstructed to have radial entries and exits, with drivers on the circulating roadway having priority (right aerial picture). With this change, the roundabout is no longer a black spot.

Old situation: tangential connected approaches | **New situation: radial connected approaches**

Figure 20: Example of reconstruction tangential connected approaches (The Netherlands)

4.3.2 Splitter islands

Splitter islands are preferably used on each leg, located and shaped so as to separate and direct traffic entering and leaving the roundabout. Care must be taken, because splitter islands applied in a wrong way can cause negotiability problems for trucks and buses. They are usually kerbed, but if there is insufficient space to accommodate a kerbed island, they may consist entirely of markings and/or an overrun area. Markings may also be used to extend a splitter island. The advantage of markings is a more flexible solution for heavy traffic.

The head of the kerbed splitter island should be set back from the side of the circulating lane by approximately 1 meter to improve the roundabout’s negotiability.

Advantages of a kerbed splitter island are:
- they can act as pedestrian or cyclist refuges, provided that they are wide enough to give sufficient safe standing space for wheelchair users, pedestrians with a buggy, or a bike;
- traffic signs, public lighting and other street furniture can be sited on a kerbed splitter island;
- splitter islands increase capacity, because they allow entering drivers to distinguish earlier between vehicles exiting the roundabout and vehicles continuing around the roundabout, to which they must give way;
- they prevent wrong-way left turns onto the roundabout.
- they help keep exiting vehicles from going too fast and encroaching on the entry lanes

The shape of the kerbed splitter island of the entry lane is very critical. There are three possible designs (see figure 21):

1. radial: the kerbline lying on a straight, parallel at the axis line through the centre of the roundabout;
2. mixed radial / tangential: the kerbline lying on an arc which, when projected forward, meets the central island tangentially;
3. tangential: a straight kerbline which, when projected forward, meets the central island tangentially.

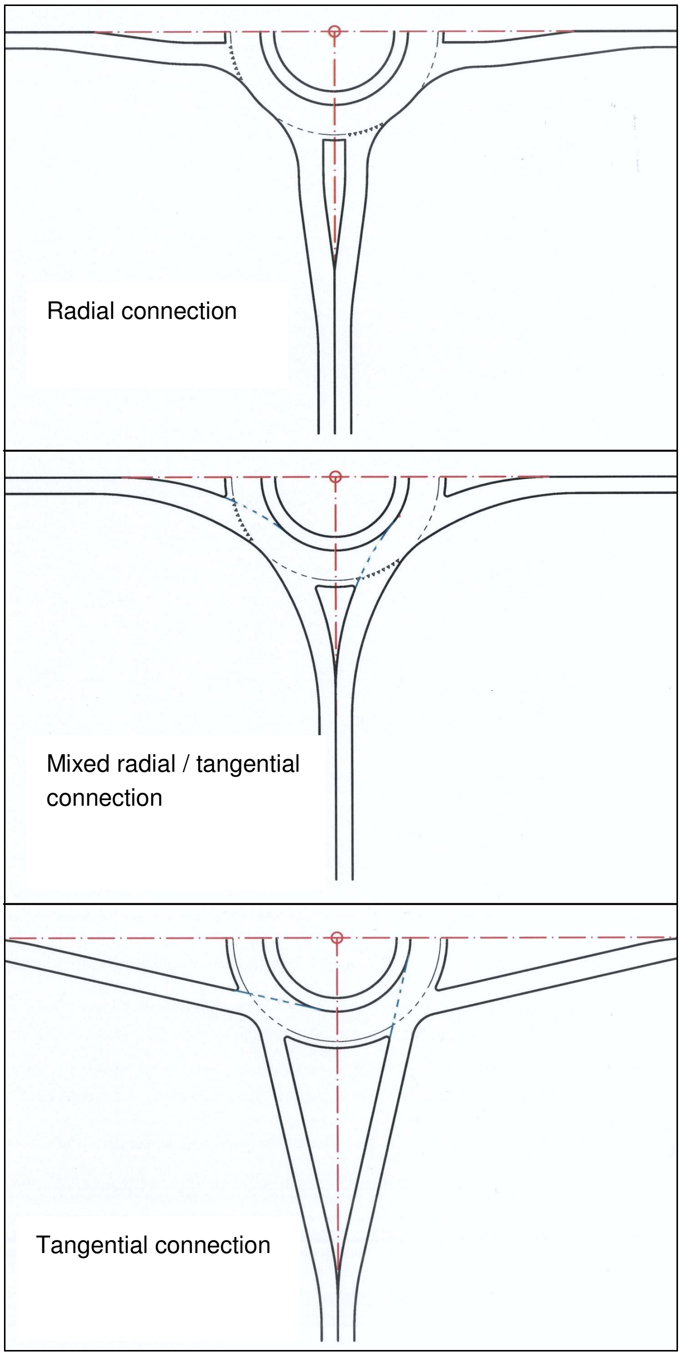


Figure 21: Design of the kerbline of the splitter island

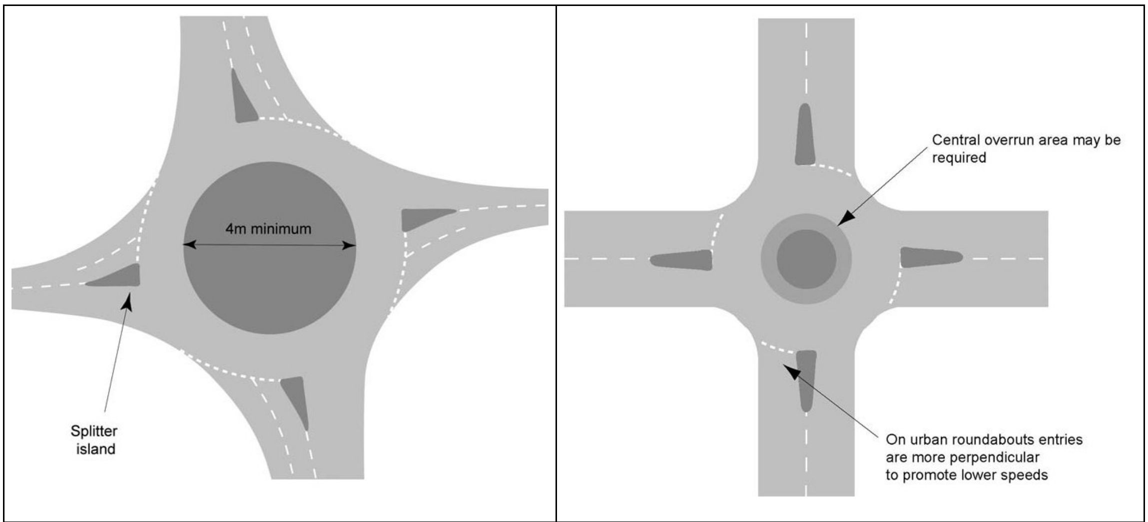
In the United Kingdom, France and Germany the design mentioned under number 2 is very common. The argument for this is that failure to do so can lead to more single vehicle accidents, especially on high speed roads. However, nowadays solution number 1 has been standardized in the United Kingdom and in the Netherlands only design number 1 is applied, for the following reasons:

- it keeps entry and exit speed low by maximizing deflection at the entry and exit points;
- this design supports the priority regime in which vehicles on the entry give way to circulating traffic;
- the angle between entry and circulating lane remains 90°, offering good mutual visibility.

If there is a (very) wide splitter island or refuge (> 3m, which can be beneficial to the capacity, see section 4.7), it is advisable to increase the diameter of the roundabout in order to create enough deflection on entry. Up to 30 m, the outer radius of a roundabout has little influence on speed and therefore on road safety.

In the United Kingdom (left side driving) different types of single lane roundabouts are standardized [7] (see figure 22):

- *Mini roundabout.* This type of roundabout does not have a kerbed central island. There is a centrally located domed circular solid road marking up to 4 m in diameter, capable of being driven over. In the Netherlands the opinion is that the mini roundabout should only be applied where two access roads cross one other. This type of roundabout is not suitable for collector roads. This manual does not give further details on the mini roundabout.
- *Compact roundabout.* This type of roundabout has a kerbed central island. The compact roundabout has single lane entries and exits. The width of the circulating carriageway is such that it is not possible for two cars to pass one other.
- *Normal roundabout.* This type of roundabout has also a kerbed central island. The approaches may be single or dual carriageway roads. This type has flared entries and exits to allow two (or three) vehicles to enter or leave the roundabout on a given leg at the same time. If so, the circulating carriageway needs to be wide enough for two or more vehicles to travel alongside each other (lanes are not marked).



Normal roundabout (United Kingdom) **Compact roundabout (United Kingdom)**

Figure 22: Types of roundabouts in the United Kingdom [7]

The normal roundabout in the United Kingdom arose historically from the 1960's, when the priority rule was to give way to traffic entering the roundabout. Designs in the United Kingdom of the normal roundabout have in principal radial legs, but the practice of flaring entries tends to create tangential or mixed tangential / radial connections in France and United Kingdom. In the Netherlands roundabout entries and exits are always radial. Swedish guidelines recommend radial entries and tangential exits. This design is acceptable if pedestrian crossings are not needed.

Entry deflection is the most important factor for road safety, because it determines the speed of vehicles through the roundabout. If the normal roundabout has more than four legs, it becomes large with the probability of higher speeds on the roundabout.

Compact roundabouts can have low values of entry and exit radii in combination with rather high entry deflection. This design has less capacity than that of the normal roundabout in the United Kingdom, but:

- the road safety is safeguarded much better;
- the movements of pedestrians and cyclist can be accommodated in a much better way (see section 4.6.1).

The capacity of a compact roundabout can be improved in various ways. The Netherlands has a strong preference for the compact single lane roundabout for reason of road safety and the available possibilities for enhancing the capacity. If more capacity is needed, the creation of bypasses (see section 4.5) or a turbo roundabout (chapter 5) may be good options.

Speed control

Good roundabout design should limit entering speeds to a maximum of 30 to 35 km/h. The higher the entering speed, the higher the risk of severe accidents. With the aid of figure 23 and two formula, the expected driving speed through the roundabout can be checked. Two measurements are important: U and L. The length L (m) is the distance between the tangent of entry radius and the tangent of the exit radius. The second measurement is U, which represents lateral deflection. The path of the vehicle is assumed to be always 1 meter away from the different curves.

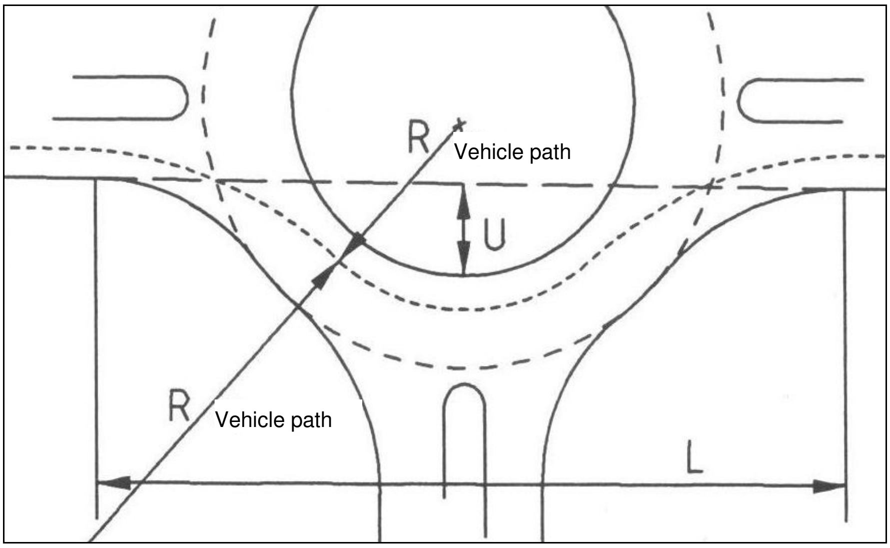


Figure 23: Speed depends of deflection [3]

With both measurements L and U in meters, the radius of the vehicle path can be calculated.

$$R_{\text{vehicle path}} = \frac{(0{,}25 \times L)^2 + (0{,}50 \times (U + 2))^2}{U + 2}$$

The design is correct if the radius of the driving path is between 22 and 23 m. The relation between the speed in the vehicle path curve and the curve radius is: $V = 7.4 \times \sqrt{R_{\text{vehicle path}}}$. If the calculated speed is higher than 35 km/h, the design must be adjusted. The formula therefore is a very practical tool to determine the effect of changing design parameters.

Figure 24 shows an example from Germany of a road speed limit 100 km/h) with two roundabouts between two villages [13]. The lines indicate the strong reduction in speed caused by the roundabouts. It illustrates the effectiveness of roundabouts in reducing speeds at places with potential hazards (crossing road users).

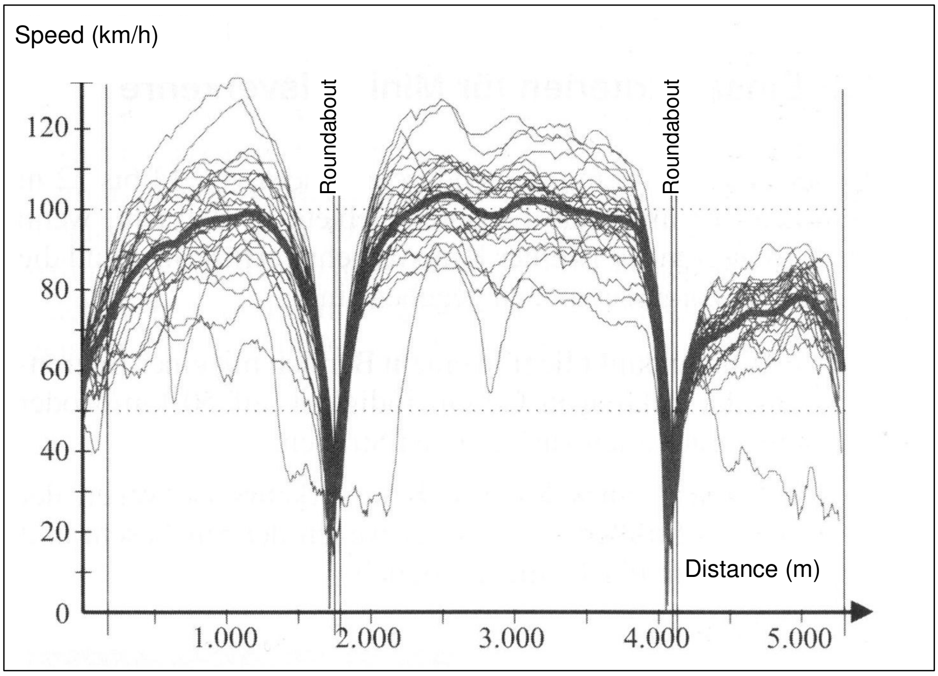


Figure 24: Speed characteristics on a road section with two roundabouts between two villages [13]

4.4 Dimensions of design elements

The following design elements determine the layout of the standard roundabout outside built-up areas:

- the outer radius (inscribed radius) of the roundabout and the radius of central island;
- the width of the circulating lane;
- the overrun area around the central island;
- the entry and exit curve radii;
- the width of the entry and exit lanes.

Table 12 and figure 25 show the Dutch standard dimensions for the single lane roundabout, whose design vehicle has a length of 15.5 m. It also shows standard dimensions for roundabouts for design vehicles whose length is 22.00 and 27.00 m.

Table 12: Overview of Dutch dimensions single lane roundabout outside built-up areas [3]

Design element	***Standard***	***Long design vehicle***	
	(m)	***22.00 m***	***27.00 m***
Outer radius (Rbu)	18.00	18.00	18.00
Inner radius (Rbi)	12.75	12.75	12.75
Circulating lane width (B)	5.25	5.25	5.25
Overrun area	1.50	3.00	4.00
Entry curve radius (Rt)	8.0[1] / 12.0[2]	12.00	12.00
Exit curve radius (Ra)	12.00[1] / 15.00[2]	15.00	15.00
Entry lane width (Bt)	4.00[1] / 3.50[2]	4.00	4.00
Exit lane width (Ba)	4.50[1] / 4.00[2]	4.50	4.50
Splitter island width (Bm)	3.00	3.00	3.00
Splitter island length (Lm)	10-15	10-15	10-15

[1]) without splitter island [2]) with splitter island

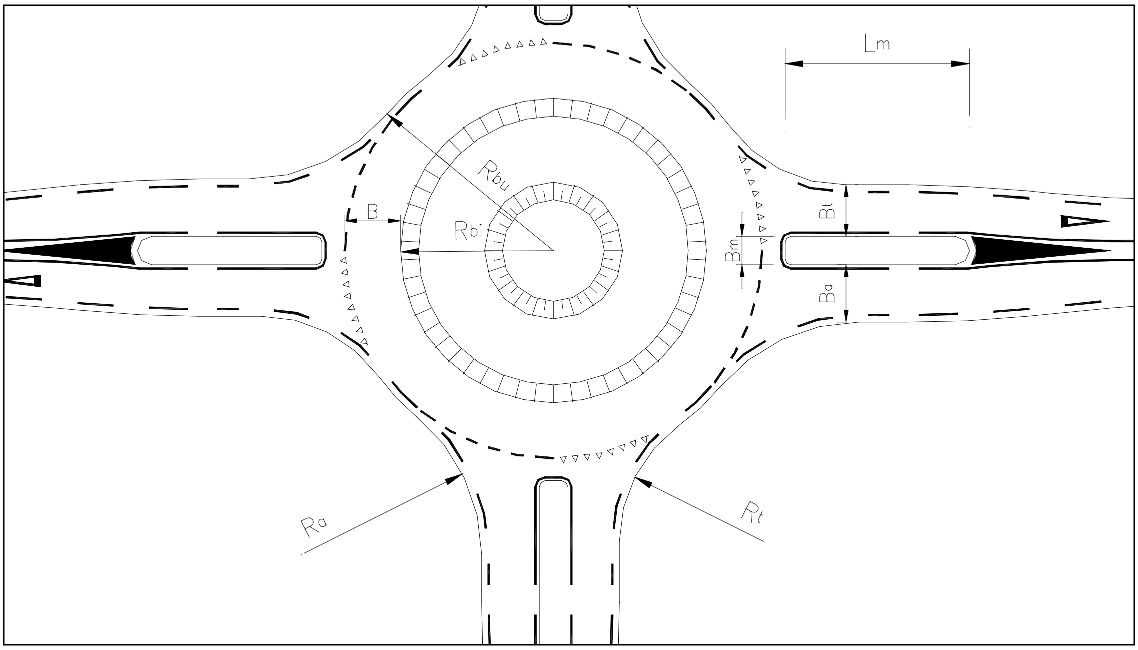


Figure 25: Design elements of single lane roundabout outside built-up areas

Outer radius

The outer radius (Rbu) is the distance from the centre of the roundabout to the outside of the pavement. It is the largest circle that can be fitted within the intersection outline (inscribed diameter). Any cyclist facilities are outside this circle. The outer radius is therefore directly related to the space available for the motorized traffic. The radius depends of the swept path of the design vehicle. The standard is based on the articulated vehicle. The Dutch inscribed diameter (= 2 R_{bu}) is 36 m; almost the same dimension as the German standard of 40 m [13] and the informal US-guideline of 30 – 40 m [12]. The United Kingdom prescribes a minimum of 28 m and a maximum of 100 m.

Research in France, Germany and the Netherlands showed that larger roundabouts have higher accident rates than smaller ones. As mentioned before, larger roundabouts result in high circulating and entering speeds which create operational difficulties (less capacity, more accidents). The circle diameter of the roundabout (=2 R_{bu}) should preferably not exceed 40 m; the maximum is 50 m. The minimum value of the circle diameter is about 28 m. This is the smallest roundabout that can accommodate the swept path of an articulated vehicle with a length of 15.50 m (the design vehicle).

Inner radius, central island

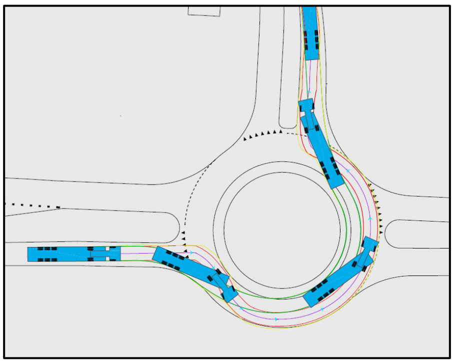
The inner radius (R_{bi}) is the radius of the central island, including the overrun area. The inner radius therefore determines more or less the visual restriction presented to entering vehicles and the negotiability of the roundabout. The inner radius determines the lateral deflection and therefore has a major influence on driving speeds on the roundabout, and therefore on road safety. Islands with circle diameters of less than 10 m (= 2R_{bi}) often permit a straight driving path, with potential for high speeds.

The central island should preferably be circular. The outer radius, the width of the circulating lane and the central island diameter are interdependent. Once any two of these are established, the remaining measurement is determined ‘automatically’. The measurements can be checked by looking at the swept path requirements of an articulated vehicle. In general this type of vehicle requires more space than other vehicles, except extra long vehicles.

The central island presents an obstruction to traffic and therefore it is necessary that it be recognizable at the required stopping sight distance. Most countries recommend deliberately obstructing forward visibility through the central island. Vegetation can be used to achieve this and to improve the aesthetic quality.

Overrun area

The overrun area is a part of the central island. Its width depends on the design vehicle and the combination of the dimensions of the other design elements. The reason for an overrun area is to keep the roundabout compact, but negotiable for articulated vehicles. This overrun area should be capable of being mounted by the articulated vehicles, but be unattractive for use by passenger cars. The gradient of the area is 1%, combined with a transitional concrete element (special kerbstone) with a gentle slope (maximum elevation difference = 0.05 m) to prevent lorries from overturning. The surface of this area is textured (rumble area).



Circulating lane

The difference between the outer and the inner radii ($R_{bu} - R_{bi}$) is the circulating lane width (B). The lane width must, on the one hand, be wide enough for the representative design vehicle to pass and, on the other hand, not so wide that it encourages excessive speeds. The circulating lane should generally be circular and of constant width. However in complex situations (lack of space or more than 4 legs), it is possible to cut the roundabout in two halves and connect these two halves with each other with short straight (tangent) segments.

The standard dimensions quoted for the outer and inner radii should not be taken as absolute figures. Larger roundabouts can also function quite satisfactorily, as long as the dimensioning of the other design elements corresponds. Figure 26 shows a graphic of the relationship between outer radius, inner radius and lane width.

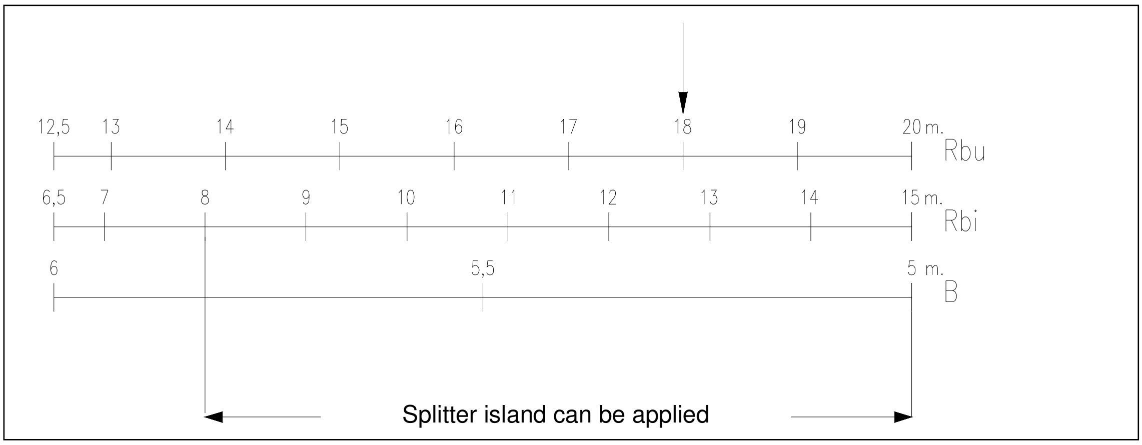


Figure 26: Relation between outer radius, inner radius and circulating lane width for a single lane roundabout

Figure 27 shows the cross-section of the roundabout, giving attention to crossfall and elevation changes. With the exception of the United Kingdom, most countries apply outward sloping crossfall on the circulating carriageway varying between 1.5 and 3%. Outward crossfall increases the recognizebility of the central island and makes it easy to construct the drainage. In addition, an outward crossfall reduces driving speed in the circulating lane.

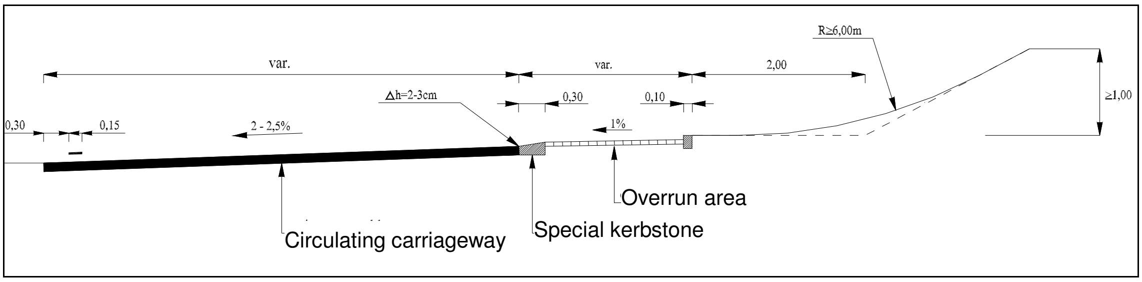


Figure 27: Cross section of a single lane roundabout

Entry angle

The entry angle is the conflict angle between the entering and the circulating traffic. The recommended range is 80° to 110°, and is preferably 90°. Smaller values may cause troubles for (older) drivers looking over their shoulder and result in too little deflection (high speeds). Larger values may give excessive deflection (difficult manoeuvres).

Entry and exit radii

Together with the width of the circulating lane and the width of the entry and exit lanes, the entry and exit radii determine the negotiability of the roundabout for the representative design vehicle. In general, it is preferable to make these radii as small as possible. More generous radii can lead to higher speeds. If needed, an overrun area next to the entry and exit curve can be added to ensure negotiability for articulated or longer vehicles. The kerb radii should be between 10 m and 15 m (Dutch guideline). The German guideline prescribes radii between 14.00 m and 16.00 m for the entry and 16.00 m to 18.00 m for the exit.

Lane width of entries and exits

The widths of the entry and exit lanes have little or no influence on circulating speeds on the roundabout, but do affect:

- the negotiability of the roundabout for buses and articulated vehicles;
- the location and ease of road crossings for cyclists and pedestrians;
- the natural perception of the motorists, when the entry is narrow and the central island is large, supports the priority rules.

Entry lane width should be between 3 and 4 m. It is not necessary to take in account a broken down vehicle (chance of broken down vehicle in this short a distance is very small). If the lane at the give way line is too wide, drivers will use the space to enter the roundabout with high speeds (increasing accident risks). The lane width of exits depends of the needed swept path, but is in typical situations between 3.75 m and 4.50 m wide.

Visibility

Drivers of all vehicles approaching the give way line must be able to see objects and vehicles on the full width of the circulating roadway. Designer should check the visibility from the entry lane at a distance of 5 m from the give way line. Excessive visibility to the left can result in high entry speeds, potentially leading to single vehicle accidents into the central island. For this reason it is advisable to raise the central island at least 1.10 m (eye level of the driver) in order to block entering drivers' view of the more distant parts of the circulating roadway. The needed sight distance is only to about 3 seconds' travel distance in advance of the conflict point, since 3 seconds is the needed gap in the circulating flow. The visibility of pedestrian crossings is another issue that needs specific attention in the design.

4.5 Bypasses

The use of a physical segregated right turn lane is a method to improve the overall capacity of the single lane roundabout where a significant volume of right turning traffic is expected. This 'shortcut' alongside the roundabout between two connecting roads is referred to as a bypass. Figure 28 shows some bypass types. The bypass is only useful when the right turning traffic flow is substantial.

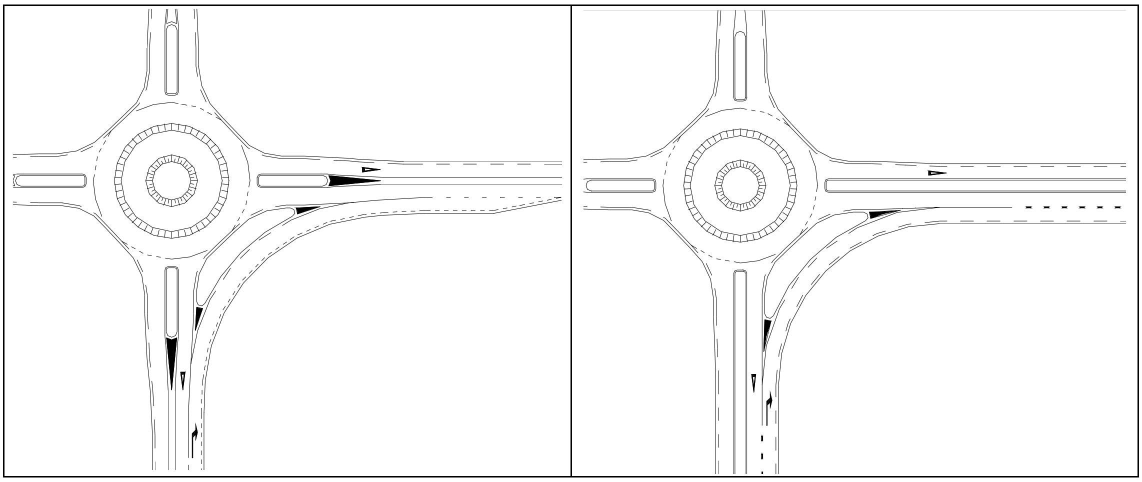


Figure 28: Types of bypass

Dual carriageway, right lane is bypass | **Separated bypass**

Figure 29: Examples of bypasses

The provision of a right turn bypass lane allows right turning traffic to bypass the roundabout, providing additional capacity for the through and left turning movements at the entry. However, it is important to consider the reversal of traffic patterns during the opposite peak time period. To determine whether a right turn bypass lane should be used, capacity and delay calculations should be performed (see section 3.3). Right turn bypass lanes might be used also at locations where the geometry for right turns is too tight to allow trucks to turn within the roundabout itself.

Bypasses are not easy to combine with parallel facilities along the road (cycle track, service road). A bypass increases the number of conflict points with pedestrians and cyclists. Moreover speeds on the bypass are generally higher than on the roundabout. Therefore it is advisable to restrict the use of bypasses to situations with no or low numbers of pedestrians and cyclists.

The radius of the right turn bypass lane should not be significantly larger than the radius of the fastest entry path provided at the roundabout. This will ensure that vehicle speeds on the bypass lane are more or less similar to speeds of traffic passing through the roundabout, resulting in safe merging movements of the two roadways. A small radius also provides greater safety in case there are for pedestrians who must cross the bypass. The bypass lane always should be separated physically from the circulating carriageway.

4.6 Special user groups

Roundabouts should accommodate all special groups of road users that may use the facility. Powered two wheelers (e.g. mopeds) and agriculture traffic generally do not dictate particular requirements. Special groups of road users are:

- pedestrians and cyclists;
- public transport;
- emergency vehicles;
- extra large vehicles.

4.6.1 Pedestrians

Roundabouts are relatively safe places for pedestrians to cross the road, because they force vehicles to slow down in order to negotiate the roundabout. Splitter islands can also act as pedestrian refuges. The types of pedestrian facilities at roundabouts are the following:

- informal crossing, only acceptable when the number of crossing pedestrians is limited;
- marked pedestrian crossing (zebra crossing);
- grade separated crossing (see section 5.1.4).

Refuge

The informal crossing and the marked pedestrian crossing (zebra crossing) can be combined with providing a splitter island as a pedestrian refuge. Pedestrians are accommodated by crossings around the perimeter of the roundabout. By providing space to pause on the splitter island, pedestrians can negotiate one direction of conflicting traffic at a time, which simplifies the task of crossing the road. The roundabout should be designed to discourage pedestrians from crossing the central island. Pedestrian crossings should be set back from the give way line by one vehicle lengths (5 m to 6 m), in order to:

- shorten the crossing distance (near the circulating carriageway the entry is wider);
- separate vehicle-vehicle and vehicle-pedestrian conflict points;
- allow the second entering driver to devote full attention to crossing pedestrians while waiting for the driver ahead to enter the roundabout.

Compared to two way priority intersections, roundabouts make it easier and safer for pedestrians to cross the road. At both roundabouts and two way priority intersections, pedestrians have to judge gaps in the (uncontrolled) stream of traffic. Because of the low vehicular speeds through a roundabout it is easier to judge the speed and, by reducing stopping distance, low speeds generally reduce the frequency and severity of incidents involving pedestrians.

Children, elderly people and people with disabilities are particularly at risk at intersections. Children (owing to their lack of traffic experience, impulsiveness or small size) and elderly people (owing to their age-related physical limitations) present challenges to the designer. Intersections must accommodate the needs of pedestrians with disabilities. Elderly pedestrians, children and the disabled find it more difficult to cross unprotected road crossings. These types of pedestrians generally prefer larger gaps in the traffic flow and walk at slower speeds than other pedestrians.

Outside built-up areas footpaths are not always available. The consequence is that the pedestrians have to walk on the road. For road safety it is recommended to create sidewalks nearby the roundabout. At roundabouts it is possible then to connect these sidewalks to road crossings, improving safety for both motorists and pedestrians.

A zebra crossing can be applied next to the roundabout (they are especially relevant if there is a bus stop). It is noted that such a zebra crossing influences the capacity of the roundabout, depending of the number of pedestrians, because with a zebra crossing drivers have to give way to pedestrians. Zebra crossings should not be used where the 85th percentile speed exceeds 50 km/h. If the 85th percentile speed exceeds 50 km/h, serious consideration should be given to speed reduction measures before installing at-grade crossings.

4.6.2 Cyclists

In most situations, cyclists have similar traffic characteristics as pedestrians. They are vulnerable and need protection to make the roundabout safer. Roundabouts without cycle paths do not provide protection or safety benefits to cyclists. Neither do bike lanes on the circulating carriageway. The complexity of vehicle interactions within a roundabout leaves cyclists vulnerable. For this reason (see figure 31), bicycle lanes within the circulating carriageway should not be used.

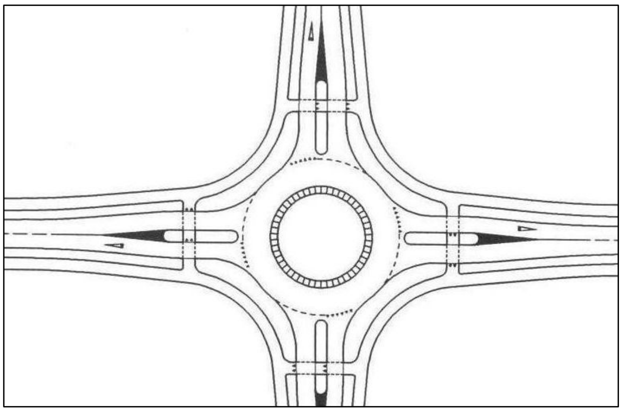


Figure 30: Cycle paths around the roundabout

A bicycle path physically separated from the circulating carriageway is preferable. It can be a shared path of sufficient width and appropriately marked to accommodate both cyclists and pedestrians around the perimeter of the roundabout. The shape of the cycle path should be rectangular, not circular, so that the path approaches entry and exit legs at right angles, in order to emphasize that cyclists have to give way when crossing a leg of the roundabout.

Bike lanes on the circulating carriageway (not recommended)

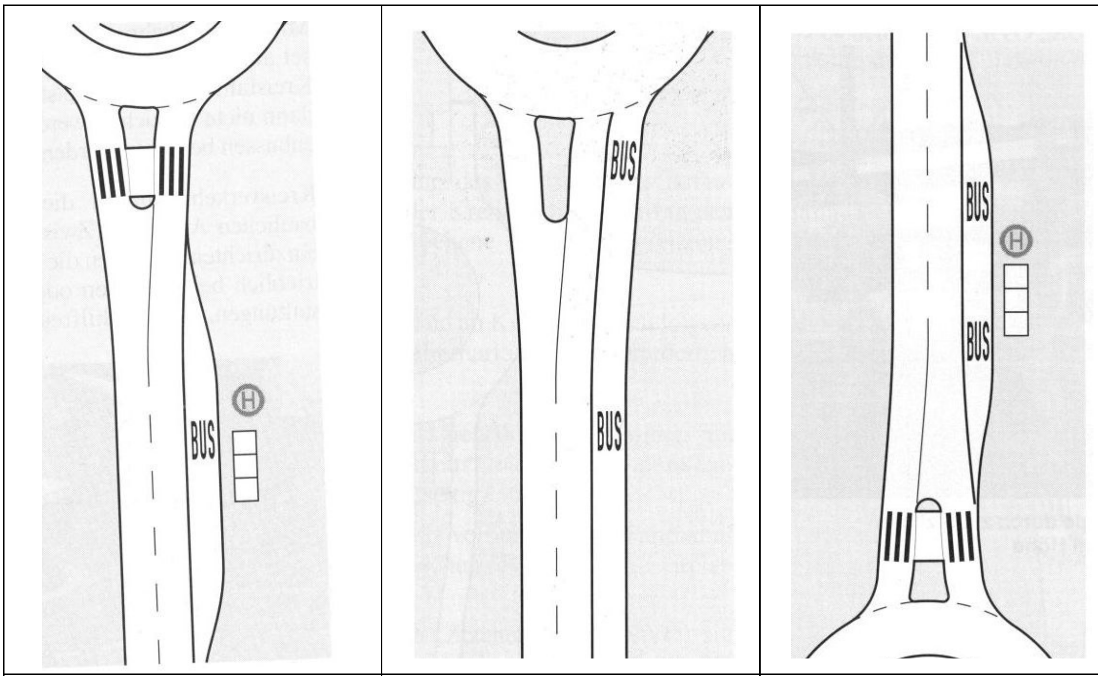
Physically separated cycle paths

Figure 31: Facilities for cyclists

4.6.3 Public transport

Transit considerations at a roundabout are similar to those at a conventional intersection. If the roundabout has been designed using the appropriate design vehicle, a bus should have no physical difficulty negotiating the intersection. To minimize passenger discomfort, if the roundabout is on a bus route, it is preferable that the roundabout be dimensioned so that scheduled buses are not required to use the overrun area.

Bus stops should be located carefully to minimize the probability of vehicle queues spilling back into the circulating roadway. This typically means that bus stops located on the far side of the intersection need to have a layby, or need to be placed downstream of the splitter island. Pedestrian access routes to the bus stop should be designed for safety, comfort and convenience. If demand is significant, such as near a station or terminus, pedestrian crossing capacity should be accounted for. Figure 32 shows examples for the location of a bus stop. A bus stop before the entry of the roundabout is preferred, as the bus already has to reduce its speed to enter the roundabout. A bus lane is useful when the entering traffic flow is close to the capacity of the roundabout; it allows buses to pass the queue by using the bus lane.



Bus stop before entry | **Bus stop on bus lane before entry** | **Bus stop after exit**

Figure 32: Bus stops nearby a roundabout [13]

4.6.4 Large vehicles

Roundabouts should always be designed for the largest vehicle that can be reasonably expected during normal operation (the ‘design vehicle’). For single lane roundabouts this requires the use of an overrun area around the central island to provide the additional width needed for tracking the trailer wheels of long vehicles. In some cases, roundabouts have been designed with gated roadways through the centre islands to accommodate oversized trucks (see figure 33).

Emergency vehicles

The passage of large emergency vehicles through a roundabout is the same as for other large vehicles and may require the use of an overrun area. On emergency response routes, the delay for the relevant movements at a planned roundabout should be compared with alternative intersection types. Just as they are required to do at conventional intersections, drivers should be educated not to enter a roundabout when an emergency vehicle is approaching on another leg. Drivers already in the roundabout, when an emergency vehicle approaches, should clear out of the circulation roadway if possible, facilitating queue clearance in front of the emergency vehicle.

Roundabouts provide emergency vehicles the benefit of lower vehicle speeds, which may make roundabouts safer for them to negotiate than signalized crossings. Unlike at signalized intersections, emergency vehicle drivers are not faced with through vehicles unexpectedly running into the intersection and hitting them at high speed.

Bypass with barrier (Netherlands) **Bypass through centre island (Poland)**

Figure 33: Examples of bypass through the centre island for extra large vehicles

4.7 Road marking, signposting and public lighting

4.7.1 Road marking

Typical pavement markings for roundabouts consist of delineating the entries and the circulating carriageway. Approach and entry pavement markings consist of give way lines, symbol markings and channelizing markings (see also figure 37).

Give way marking
Basically, the traffic in a roundabout has right of way. Therefore, give way white triangles (sharks' teeth) should be used to demarcate the entry approach from the circulating roadway. The symbols should be located along the inscribed circle at all roundabouts. No sharks' teeth should be placed to demarcate the exit from the circulating roadway, but a dotted line should also be located along the inscribed circle to guide motorists who are not exiting.

Road markings
Outside the built up area, a 'symbolic' give way road marking can be used upstream of the give way line, as shown in Figure 34. This road marking reinforces the give way situation. Pavement markings are provided around raised splitter islands to enhance driver recognition of the changing roadway. For small splitter islands, the island may consist of pavement markings only.

Pedestrians
Because the pedestrian crossing at a roundabout should be located away (> 5 m) from the give way line, it is important to channelizing pedestrians to the appropriate crossing location, even when pedestrians have

no right of way (informal crossing). These markings should not be construed as a safety device. The markings provide guidance for pedestrians in navigating a roundabout and provide a visual cue to drivers where pedestrians may be within the road area. The channelizing markings are 0.10 m wide and have a length of 0.3 to 0.6 m. The gap between the lines is the same as the line length. The crossing markings should be installed across both the entry and exit of each leg and across any right turn bypass. The markings should be aligned with the ramps and the pedestrian refuge in the splitter island and have markings that are generally perpendicular to the flow of vehicular traffic.

It is also possible to give pedestrians priority by using a zebra crossing. The zebra crossing provides a higher degree of visibility than a traditional transverse crossing marking in roundabout applications. However, outside built-up areas such provisions are not preferred, as indicated in section 4.6.1. Zebra crossings should not be used where the 85th percentile speed at the crosswalk exceeds 50 km/h.

Give way road marking (Poland) **Give way signs (France)**

Figure 34: Give way road marking and signs

Cyclists

If cyclists use a separate cycle path and the cyclists have no right of way, the crossing should be indicated by cannelized markings. These markings are 0.10 to 0.20 m wide and have a length of 0.3 to 0.6 m. The cycle path should have give way road markings.

4.7.2 Signposting and signing

Signposting

At roundabouts with or without splitter islands, a central signpost is located in the centre island. To make the signs better visible at night, the signs have to be made of retro reflective material. To prevent insecure driving, road users need to know what exit to take on a roundabout. To accomplish this, signposts have to be placed well in advance of the roundabout (see figure 35). Signposts are also necessary on the exits.

Signing

To increase the visibility of the centre island outside built-up areas, a sign with the driving direction combined with a warning fence can be placed directly across the approaching leg (see figures 36 and 37). A give way sign is placed just before the give way road markings, often placed on both sides of the entry lane. In situations where the roundabout can be unexpected for approaching road users it is preferred to place a warning sign ‘roundabout’ 150 to 200 m before the roundabout.

Signposting (the Netherlands)

Signposting (France)

Figure 35: Signposting in advance of the roundabout

Signing on splitter island and central island (France)

Signing on central island (the Netherlands)

Figure 36: Give way signs on both sides of entry

4.7.3 Public lighting

Lighting is commonly used at roundabouts because the central island presents an obstacle to traffic that must be seen at the required visibility distance. At night with only (dimmed) headlights, this will not be possible. For a roundabout to operate satisfactorily, a driver must be able to enter the roundabout, move through the circulating traffic and diverge from the circulating flow in a safe and efficient manner. To accomplish this, a driver must be able to perceive the general layout and operation of the intersection in time to make the appropriate manoeuvres. Adequate lighting should therefore be provided at all roundabouts. At night the roundabout has to be as visible as at daytime.

The positioning of the public lighting must make the roundabout recognizable. If the roads leading to the roundabout are not lighted, it is better to place lighting on the roads as an introduction to the roundabout. At the roundabout itself it is preferable to place the lighting outside the roundabout. In this way misreading of the design is prevented and the roundabout is better noticed.

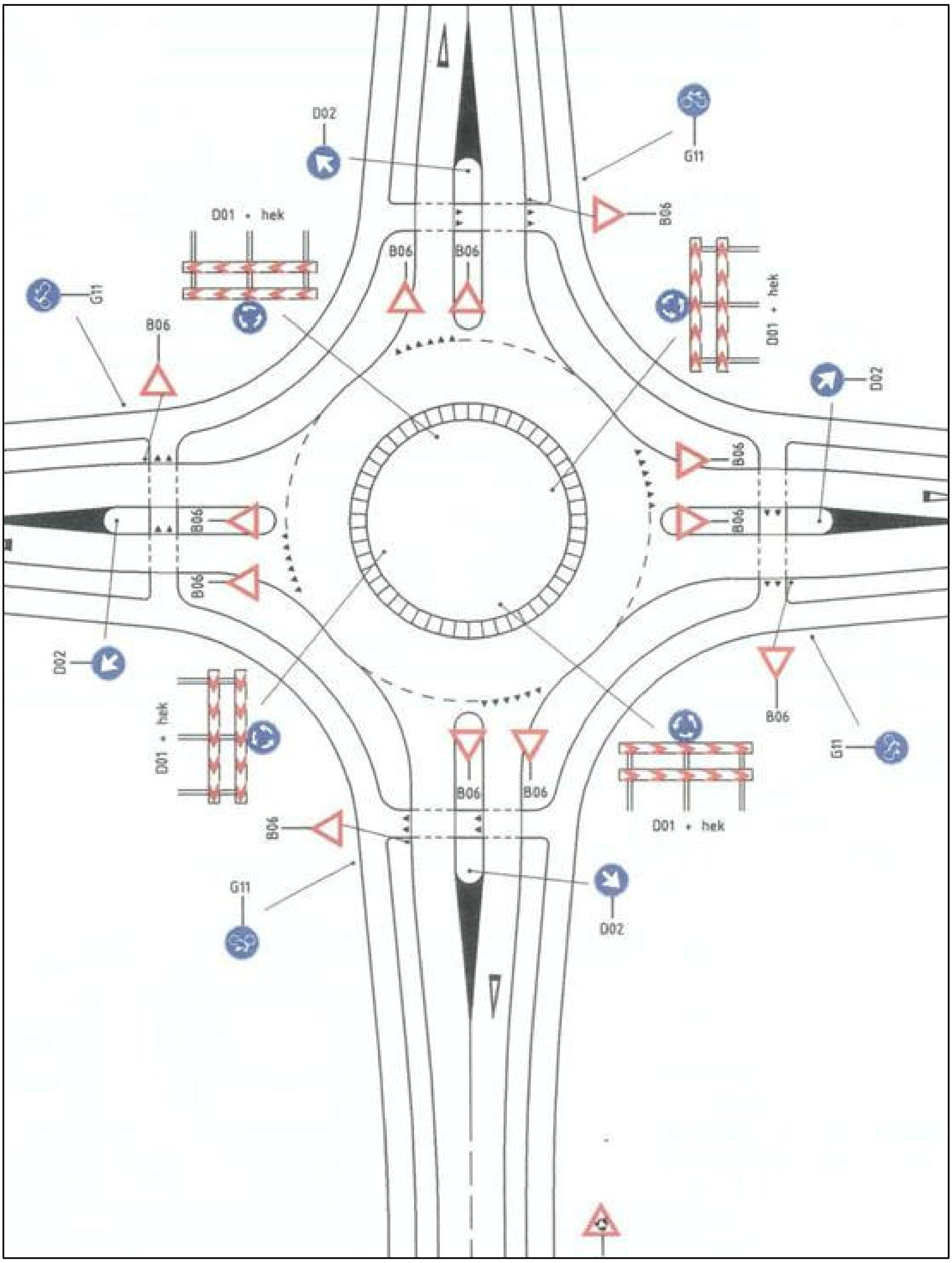


Figure 37: Signing for roundabouts in the Netherlands [3]

Additional recommendations with regard to lighting are:

- Outside built-up areas the connecting roads have to be lighted over at least 80 to 100 m (approximately 3 light posts). This helps drivers to adapt their vision from the illuminated environment of the roundabout back into the dark environment of the exiting roadway, which takes approximately 1 to 2 seconds. In addition, no short distance dark areas should be allowed between two consecutive illuminated areas.
- To accentuate the (circular) shape of the roundabout normally eight light posts are needed.
- Good illumination should be provided on the approach to the splitter islands, at all conflict areas where traffic is entering the circulating flow, and at all places where the traffic exits.
- Special consideration should be given to lighting pedestrian and cyclists crossings.
- Ground level lighting within the centre island that shines upwards towards objects in the centre island can improve the visibility of the roundabout.
- With regard to the placement of the public lighting poles, the movement of large trucks and buses need to be considered.
- The centre island has to be clearly recognizable. Lighted signposting therefore is preferred.

5 DESIGN OF MULTI LANE AND TURBO ROUNDABOUTS

Multi lane roundabouts are seen in many countries. The main reason for designing and constructing a multi lane roundabout instead of a single lane roundabout is the higher capacity. An important point of concern related to the design of multi lane roundabouts is the overall road safety, especially the safety of vulnerable road users such as cyclists and pedestrians. Experiences in the Netherlands led to the conclusion that performance with respect to both capacity and road safety are disappointing. Turbo roundabouts, which are multi lane roundabouts with spiral road marking and separated circulating lanes, perform much better in capacity and safety, while they do not need any additional space. Therefore, in the Netherlands, multi lane roundabouts are no longer being built, and existing multi lane roundabouts will be reconfigured as turbo roundabouts. For this reason this chapter also focuses on the design of turbo roundabouts (see section 5.2). However, to be complete, first there is a description of the conventional multi lane roundabout.

5.1 Conventional multi lane roundabout

5.1.1 Characteristics

The main physical characteristics of multi lane roundabouts are:

- either two or sometimes three lanes on the roundabout, or a broad unmarked roadway wide enough for vehicles to operate side by side;
- lanes on the roundabout are circular (not spiral);
- legs have one or two entry and exit lanes.

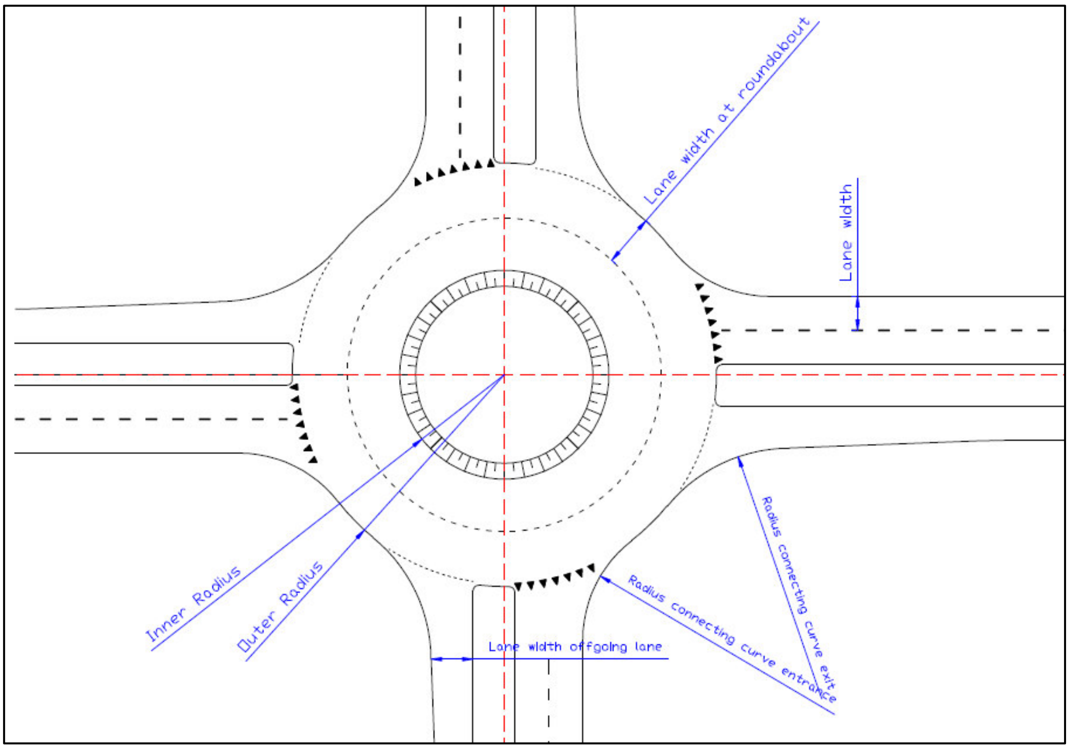


Figure 38: Former standard design multi lane roundabout in the Netherlands

Figure 39: Multi lane roundabout (the Netherlands)[2]

Figure 40: Multi lane roundabout (United States)[3]

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[2] This two lane roundabout does not comply with the (previous) Dutch standard, due to the two lane exit.

[3] Although it is recommended in the USA to use no markings on the circulating carriageway, it seems that most existing and planned multi lane roundabouts do have it.

Probably the most important disadvantage of a multi lane roundabout is that it offers the possibility of passing through the roundabout in different ways. Especially during low traffic periods, drivers tend to follow the highest speed path by changing lanes twice, as shown in Figure 41, lowering safety. Drivers often follow improper or unexpected paths through the roundabout, creating weaving conflicts and cut-off conflicts near exits, as shown in Figures 42 and 43. That might cause unexpected behaviour and several conflicts and therefore potential danger.

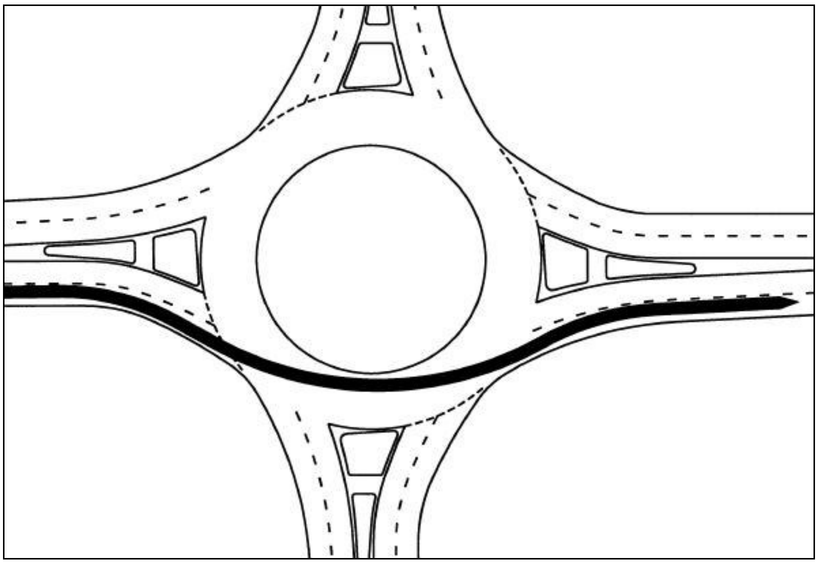


Figure 41: Quickest way to pass a multi lane roundabout [12]

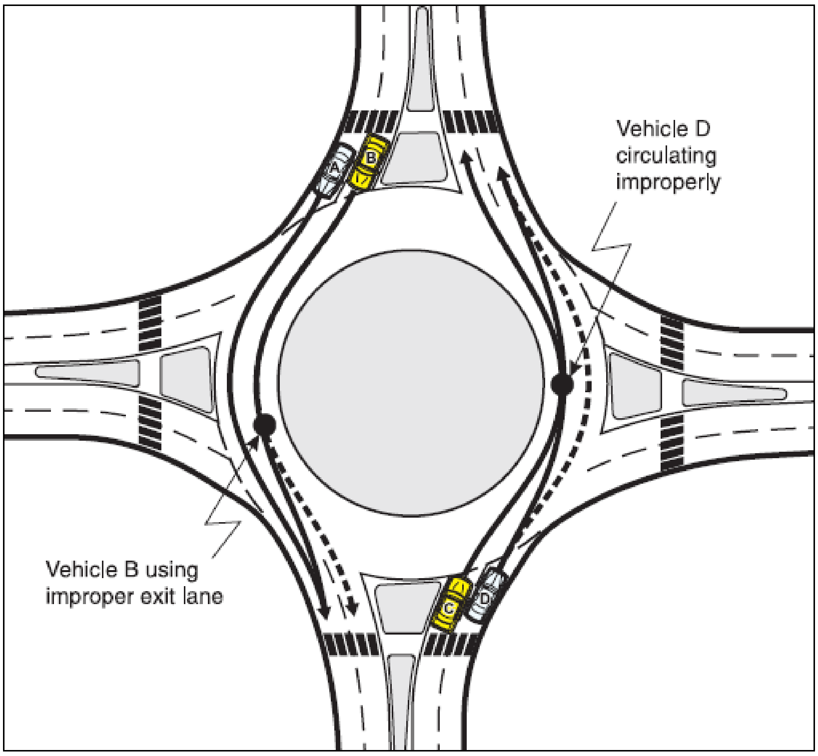


Figure 42: Improper lane use at multi lane roundabouts [12]

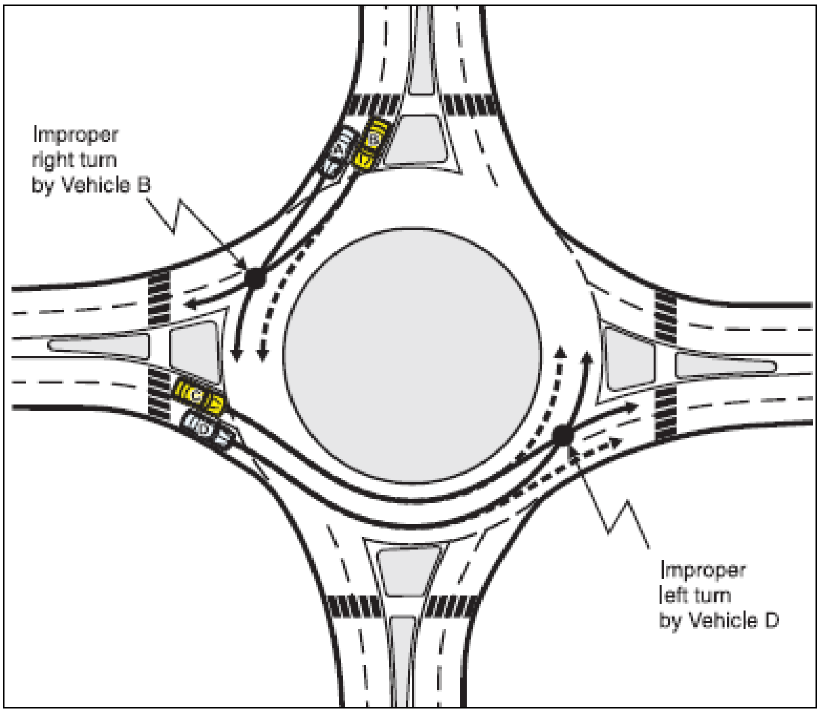


Figure 43: Improper turn conflict at multi lane roundabout [12]

Also, on multi lane roundabouts the inside lane tends to be underused because the exit from the roundabout is always on the right; therefore, the added circulating lane adds less to capacity than might be expected.

If in spite of the disadvantages, if a multi lane roundabout is built, it is important that the designer pays attention to:

- *Speed:* the speed on the roundabout should be reduced. Therefore the connection of the legs should always be radial (see section 4.3). But at multi lane roundabouts good lane use, necessary to get the full speed reduction from deflection on entry, is hard to obtain. In some countries the speed of approaching vehicles is reduced before they enter the roundabout by speed humps or axis offsets (slight curves).
- Conflict points: the number of conflict points should be limited to the minimum. Proper signing, well before entering the roundabout, can minimize the number of incorrect lane choices and thereby the number of lane changes on the roundabout itself.

5.1.2 Design parameters

When dimensioning the various design elements the following principle should be applied:

- the dimensions of the lane width at the entry should be based on the requirements of two trucks driving parallel;
- the dimensions of the central island and the width of the entries and exits must be related to the desired speed on the roundabout. In the Netherlands this used to be 40 to 45 km/h. In the USA a maximum entry design speed of 50 km/h is recommended for two lane roundabouts outside built-up areas.

Table 13 gives an overview of the Dutch design criteria. The deflection of through traffic at the roundabout is based on the dimensions of the cross section at the entry, with a splitter island width of 2.50 m and a carriageway width of 7.00 m. The design of the central island is in principle identical to that of the single lane roundabout. When applying a two lane roundabout, a splitter island or median should always be applied on the connecting roads. With an outer radius of 29.00 m, an inner radius of 20.00 m, two lanes in the entry and a median of 2.50 m a passenger vehicle may negotiate the roundabout at approximately 38 km/h. In the USA the comparable measures are given in table 14 [12].

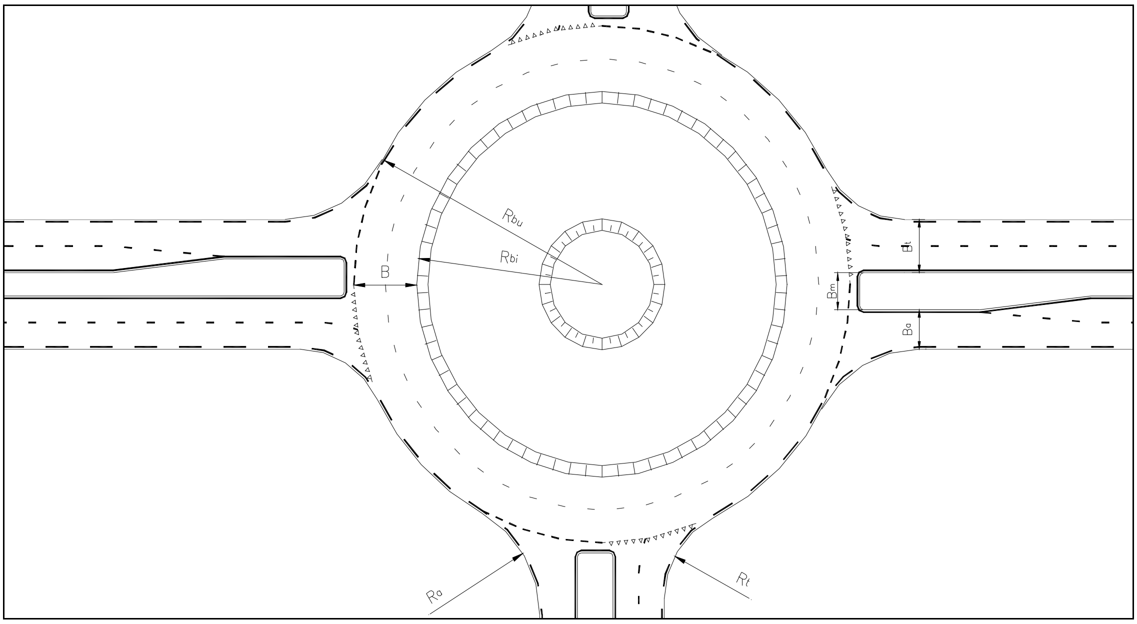


Figure 44: Design parameters multi lane roundabout

Table 13: Dimensions for two lane roundabout outside built up area [3]

Design element	***Dimensions (m)***				
Outer radius (Rbu)	20.00	25.00	29.00	33.50	38.00
Inner radius (Rbi)	10.00[1]	16.00[1]	20.00	25.00	30.00
Carriageway width (B)	10.00	9.00	9.00	8.50	8.00
Entry curve (Rt)	12.00	12.00	12.00	12.00	12.00
Exit curve (Ra)	15.00	15.00	15.00	15.00	15.00
Entry (single lane)	4.00/3.50[2]	4.00/3.50[2]	4.00/3.50[2]	4.00/3.50[2]	4.00/3.50[2]
Exit (single lane)	4.50/4.00[2]	4.50/4.00[2]	4.50/4.00[2]	4.50/4.00[2]	4.50/4.00[2]
Entry (two lane)	lane[3]	lane[3]	lane[3]	lane[3]	lane[3]
Exit (two lane)	lane[3]	lane[3]	lane[3]	lane[3]	lane[3]

[1]) test the speed on the roundabout with these dimensions

[2]) depending on whether there is any heavy or exceptional large vehicle

[3]) depends on the standard lane width

Radius of the inner circle

The relation between the speed and the radius of the inner circle is not the same as with single lane roundabouts. Cars will pass through a multi lane roundabout with higher speed, because the entries and exits are wider. Preferably the radius of the inner circle should be between 25 and 30 meter. For example, with an inner circle of 20 m and an outer circle of 29 m, a two lane entry and a middle island of 2.5 m, the speed of passenger cars is about 38 km/h. With a smaller radius of the inner circle the speed increases quickly because there is little lateral deflection. With an inner circle of more than 30 m the speed increases a little because the radii in the driving line are easier to ride.

Table 14: Dimensions of multi lane roundabouts in the USA [12]

Design element	**Minimum (m)**	**Maximum (m)**	**Remarks**
Outer circle radius	22.5	27.5	Inside built-up area
	27.5	30	Outside built-up area
Inner circle radius	12.7	26.3	
Width of carriageway	8.7	9.8	
Entry curve	30	60	Inside built-up area
	40	80	Outside built-up area
Exit curve	-	-	
Width entry (single lane)	4.3	4.9	
Width exit (single lane)	-	-	
Width entry (double lane)	6	-	Additional lane or flaring
Width exit (double lane)	-	-	

Entry and exit lanes
Two lane roundabouts can be realized with either single lane or two lane entries and exits. Single lane entries are not useful, because of the strong influence of entry lanes on the capacity of the roundabout; unless there are multi lane entries, the capacity will not (significantly) exceed the capacity of a single lane roundabout. Also the number of exit lanes may influence the traffic flow. In France, there are the following criteria for using two lane exits instead of the usual single lane exit [26]:

- the exiting traffic volume is over 1200 pcu/h;
- the exiting traffic volume is over 900 pcu/h, as well as three times higher than the circulating traffic.

In most countries entries and exits of (multi lane) roundabouts are connected tangentially to the circulating carriageway. In the Netherlands tangential entries and exits for multi lane roundabouts are strongly advised against. The choice between radial or tangential entry and exit lanes is even more important for multi lane roundabouts then it is for single lane roundabouts, because of the larger dimensions of the multi lane roundabout. Tangential entries may increase the capacity, but because of the higher speeds they permit for entering and exiting traffic, the accident probability is also higher. It is especially important to limit the speed on entry. For that reason in the USA they consider a tangential alignment of the exit lane as acceptable, while a tangential alignment of the entry lane is not acceptable.

Other design parameters (such as connecting radius of entries and exits, dimensions of splitter islands) are similar to those of single lane roundabouts (see chapter 4). This is valid not only for the Netherlands, but also, for example, for the USA, the United Kingdom, France and Germany.

5.1.3 Marking, signposting and public lighting

Multi lane roundabouts use the same basics for road markings, signposting and public lighting as single lane roundabouts (see chapter 4). The circulating lanes on the roundabout are marked as concentric circles. Marking and signposting needs more attention in order to make as clear as possible to the road users what they may expect.

5.1.4 Special user groups

Pedestrians and cyclists

Pedestrians and cyclists should not use multi lane roundabouts. At grade crossings of two lane entries and especially two lane exits should be avoided. Pedestrians and cyclists should be provided routes that bypass the roundabout, or given a grade separated crossing, via either a bridge or a tunnel. For social safety reasons a bridge is preferred. However bridges require more space than tunnels and involve larger differences in elevation for pedestrians and cyclists to overcome, and therefore require longer ramps. Tunnels in which the crossing road is raised can also be an acceptable solution. When the floor of the tunnel is no more than 2 m below ground level the view into and through the tunnel will remain sufficiently clear.

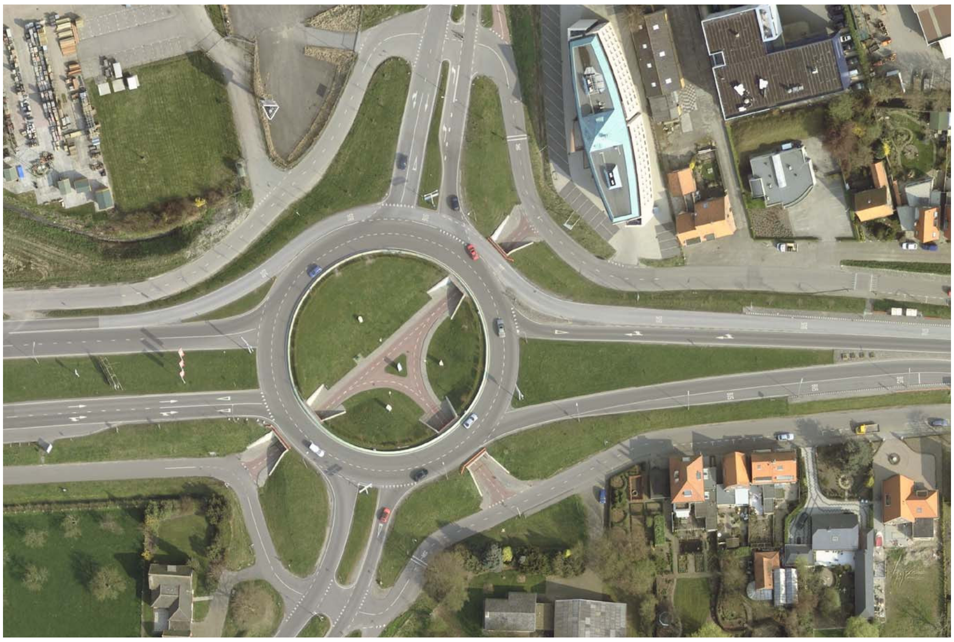


Figure 45: Example bicycle underpasses at a roundabout (the Netherlands)

Other slow traffic (e.g. agricultural vehicles) will attend to decrease roundabout capacity, and create additional conflicts, because slow traffic tends to use the outer lane on the roundabout, even when turning left. Therefore slow traffic should be given alternative routes so that it can avoid multi lane roundabout intersections.

Public transport

For public transport it is possible to add separate entry and or exit lanes, and even a separate lane on the roundabout itself. However, separate lanes (entry, exit, or within the roundabout) introduce additional conflict points and therefore potentially decrease road safety. Emergency traffic could use the separate bus lanes as well.

Exceptional transport

For exceptional and oversized transport no special features are required. The available manoeuvring space will be sufficient, and if necessary oversized vehicles can use both parallel lanes on the roundabouts.

5.2 Turbo roundabouts

As stated before, in the Netherlands multi lane roundabouts are no longer built, and existing multi lane roundabouts will be reconstructed into turbo roundabouts. The main reason is the disappointing performances of multi lane roundabouts on both capacity and road safety.

Turbo roundabouts are almost only used in the Netherlands. In 2007 over 70 of such roundabouts were in operation. One (experimental) example is known in Baden Baden in Germany. The first experiences in Germany are slightly positive. Differences in design details, especially the absence of raised lane dividers, may be the cause of an unexpected high number of accidents at one of the entries. Due to the minimal number of turbo roundabouts in other countries the following is based on Dutch experiences only [5].

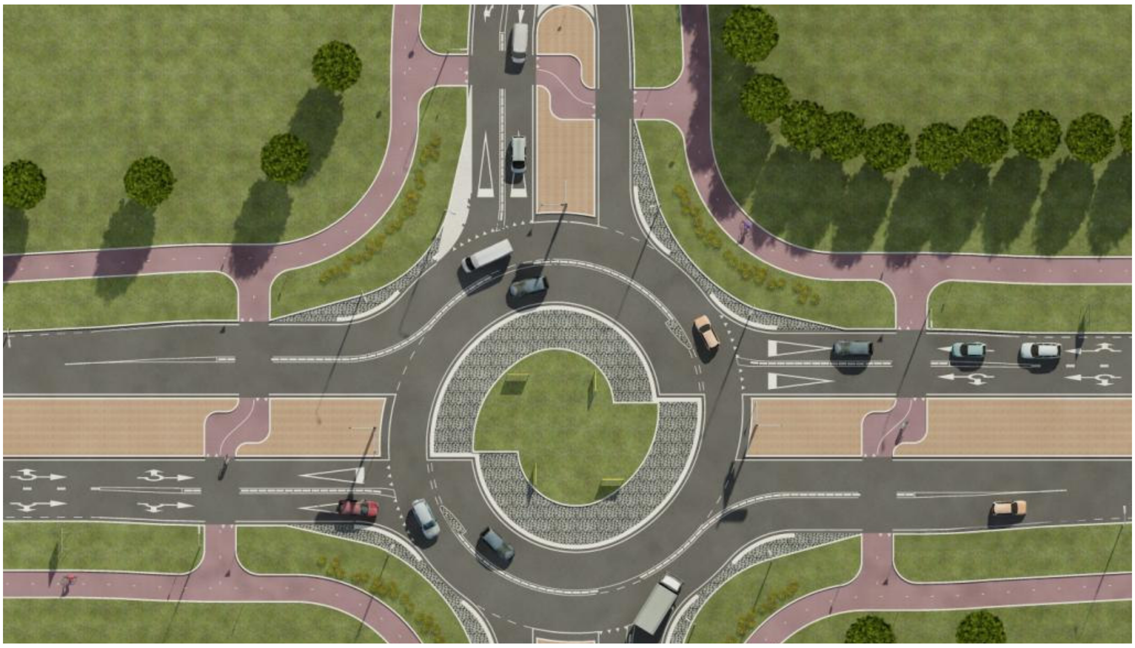


Figure 46: Standard layout of a turbo roundabout

5.2.1 Characteristics

A turbo roundabout is a multi lane roundabout with spiral road markings and separated lanes, at which road users have to choose the correct lane before entering the roundabout, in order to leave it in the desired direction. The main characteristics of a turbo roundabout are (see figure 47):

1. a turbo roundabout has more than one lane;
2. the correct lane has to be chosen before entering the turbo roundabout;
3. entering traffic has to give way to circulating traffic, which is limited to a maximum of two lanes;
4. within the roundabout itself no weaving or cutting is possible;
5. the roundabout can only be left via the previous chosen lane.

This type of multi lane roundabout has the following advantages:

- a surveyable situation when a driver enters the roundabout: drivers need only to give way to traffic in a maximum of two well-demarcated lanes;
- no risk of accidents due to lane changing on the roundabout;
- low driving speed through the roundabout because of raised lane dividers.

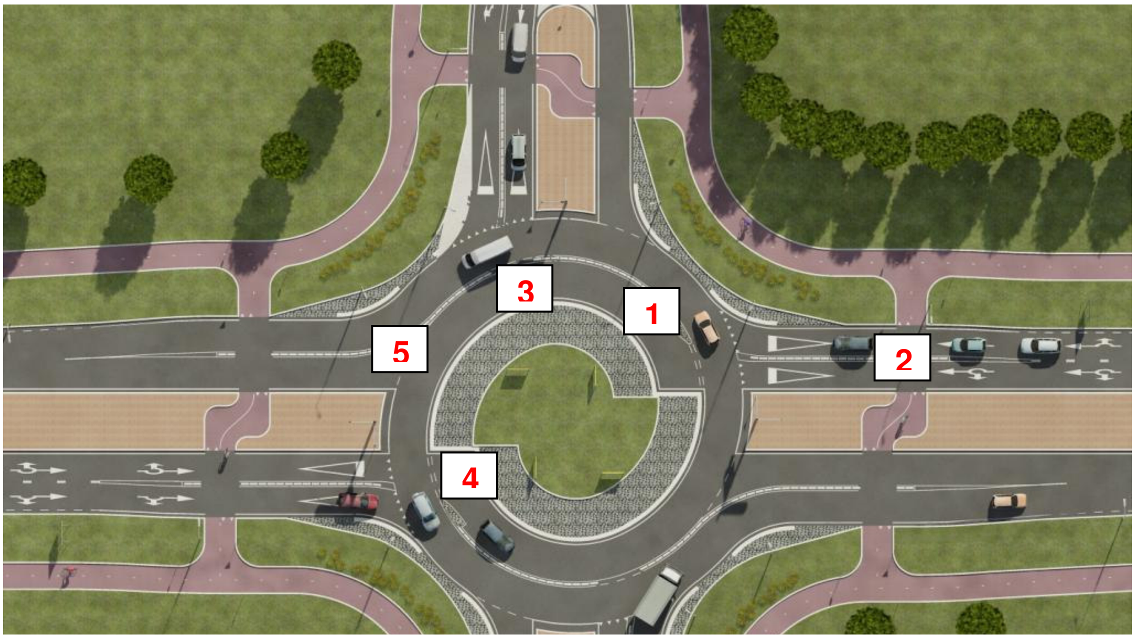


Figure 47: Main characteristics turbo roundabout

The main reasons to choose a turbo roundabout rather than other intersection types are:

- Increase capacity of the intersection. The capacity of a turbo roundabout is higher than a single lane roundabout (1½ to 2½ times as high) or a two lane roundabout (1 to 1½ time as high).
- The capacity of a turbo roundabout is equal or higher than a signalized intersection. The delays are less than at a signalized intersection.
- Increase road safety on the intersection. A turbo roundabout is safer than a give way intersection (± – 70% in fatal accidents or accidents with hospital treated injuries) and safer than an intersection with traffic signals (about – 50% reduction in fatalities and hospital-treated injuries), although not as safe as a single lane roundabout (turbo roundabout: 20% to 40% greater accident rate).
- The spatial need (m^2) of a turbo roundabout is about the same as a signalized intersection (assuming that the signalized intersection would also allow two trucks driving in parallel, in all directions).
- The construction costs of a turbo roundabout are higher than an intersection with traffic signals, but the life cycle costs and social costs are less.

The capacity of a turbo roundabout is about 3,500 to 4,500 pcu/h, for a roundabout with a diameter of about 50m. The capacity of a three-leg turbo roundabout is 5,500 pcu/h. The driving speed is low in comparison to normal signalized intersections or two lane roundabouts (see figure 48).

Five types of four-leg turbo roundabouts can be distinguished, based on differing number of entry and exit lanes and bypasses. The need for these variations has mainly to do with differences in the distribution of traffic volume over the legs of the intersection:

- the basic turbo roundabout (figure 49);
- the egg roundabout (figure 50);
- the knee roundabout (figure 51);
- the spiral roundabout; (figure 52);
- the rotor roundabout. (figure 53).

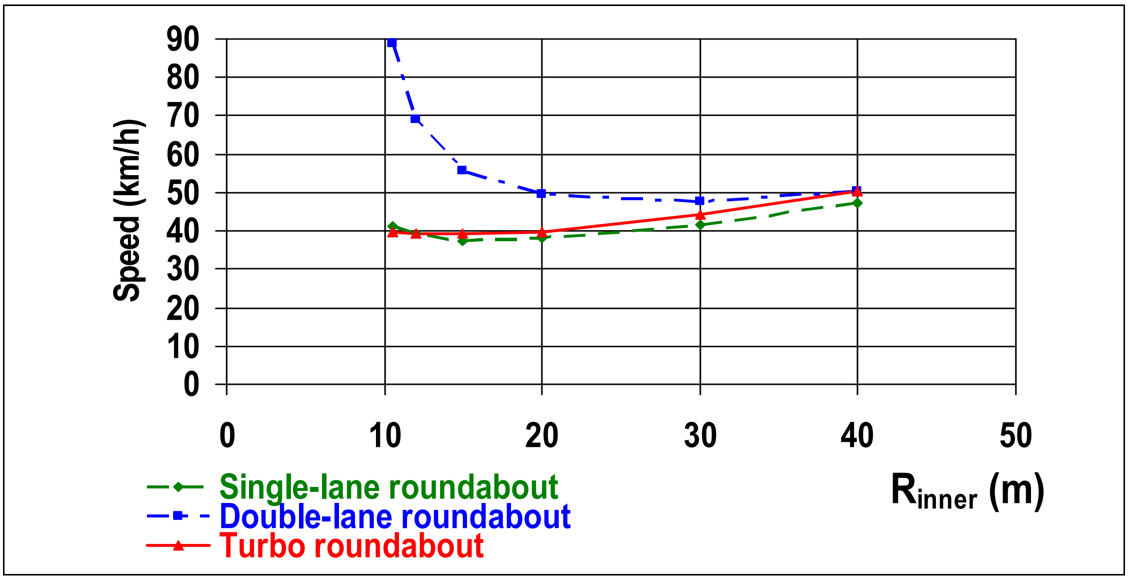


Figure 48: Relationship between speed and type of roundabout (width of splitter island = 7 m) [15]

The standard designs of these types of turbo roundabouts are given later in this section. Relative traffic volumes for the chief movements affecting the roundabout design are represented by the thickness of the blue arrows. When available, the capacity is also shown.

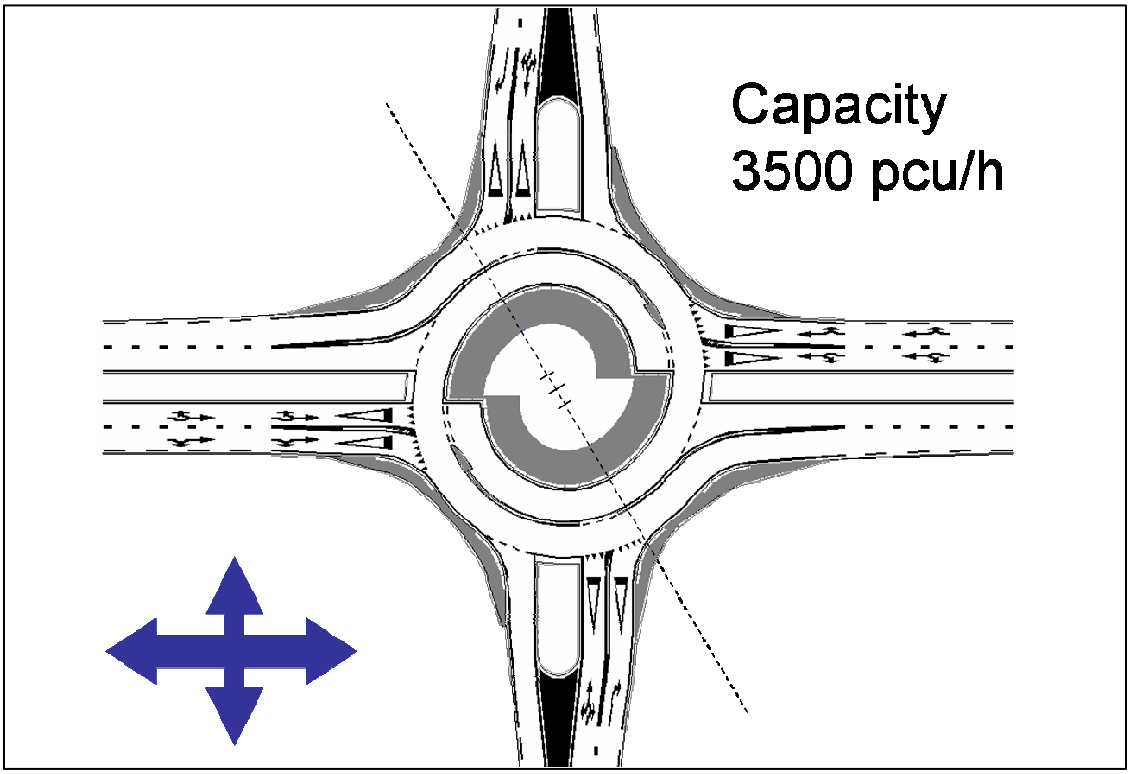


Figure 49: Basic turbo roundabout

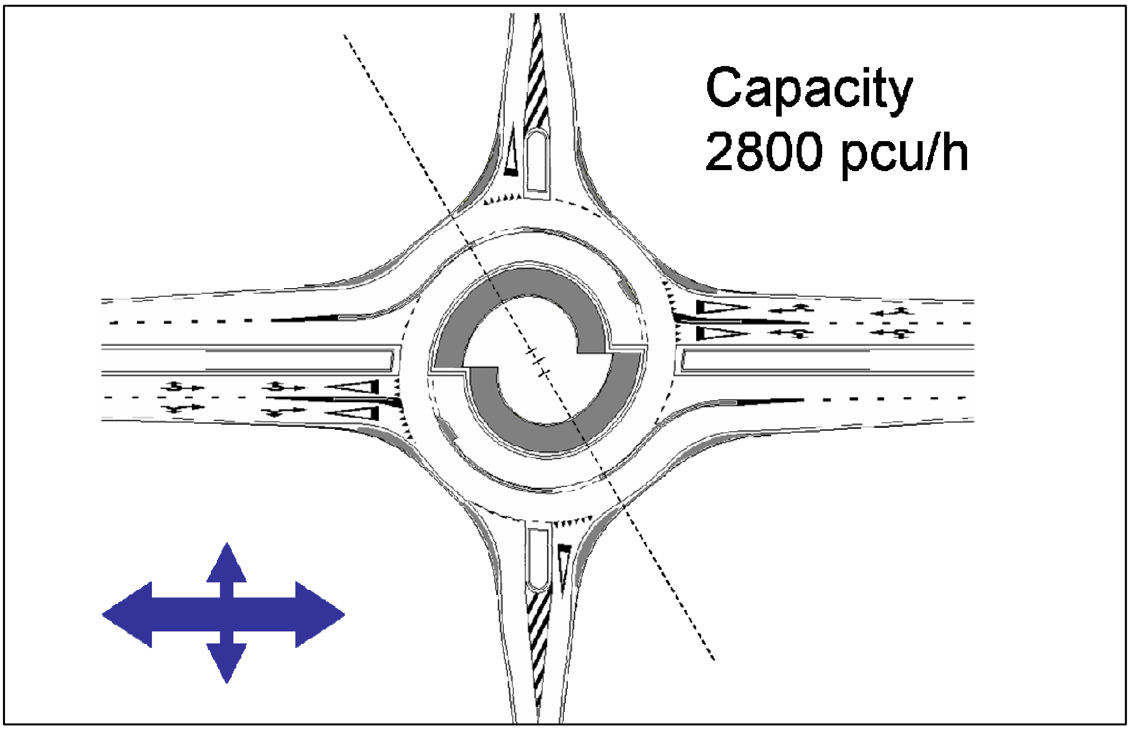


Figure 50: Egg roundabout

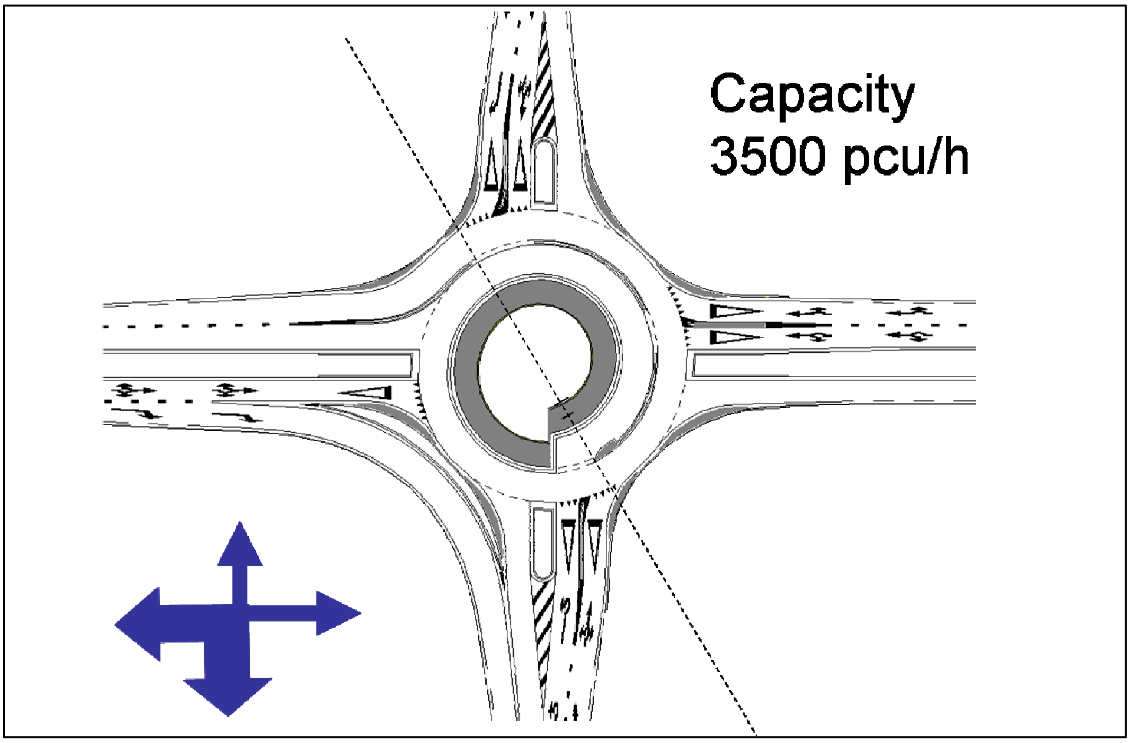


Figure 51: Knee roundabout

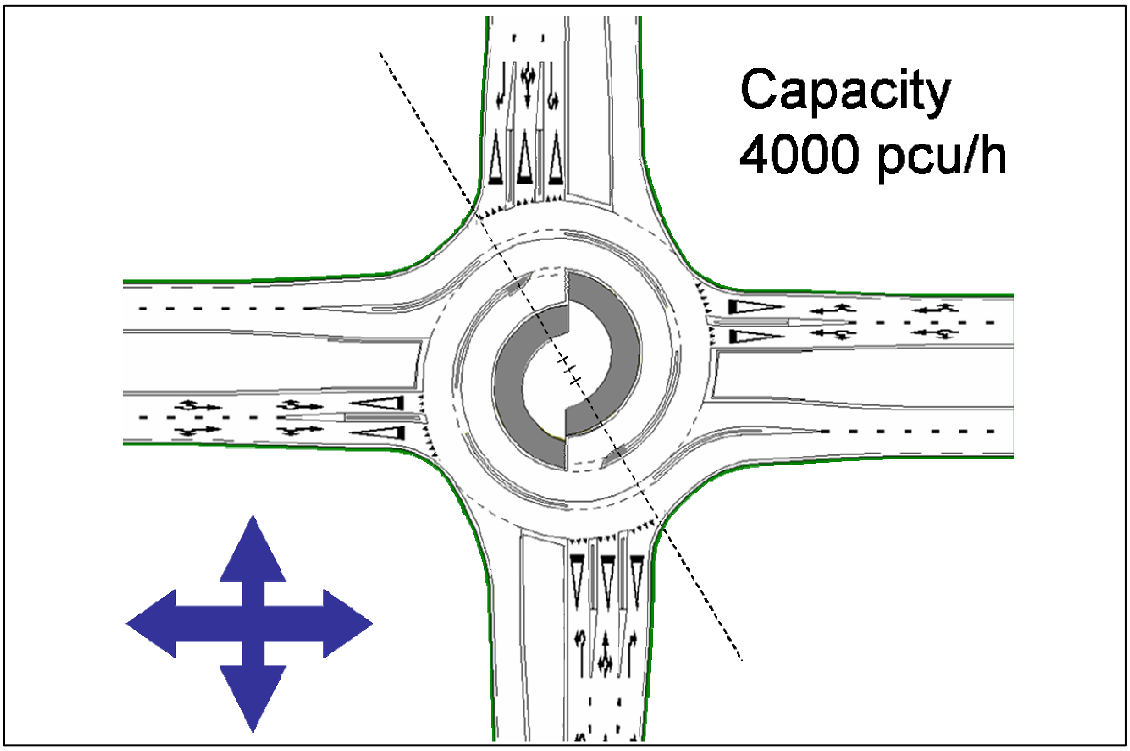


Figure 52: Spiral roundabout

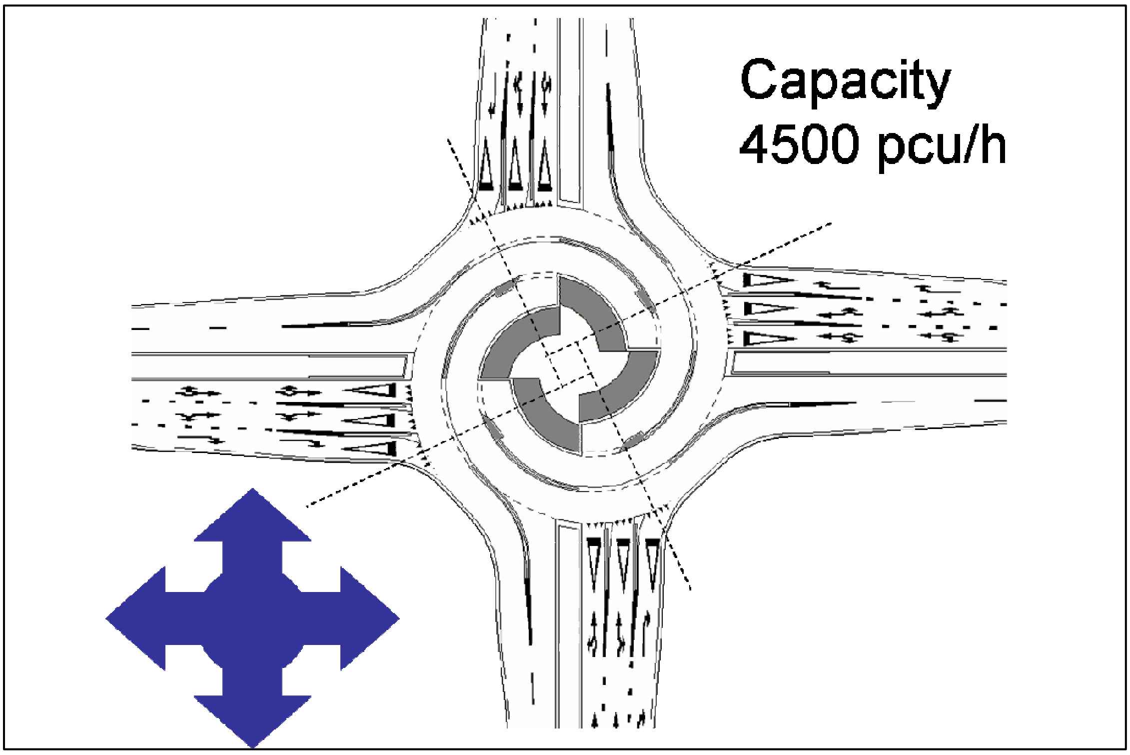


Figure 53: Rotor roundabout

For three-leg roundabouts, there are only two types of turbo roundabouts:

- stretched-knee roundabout (figure 54);
- star roundabout (figure 55).

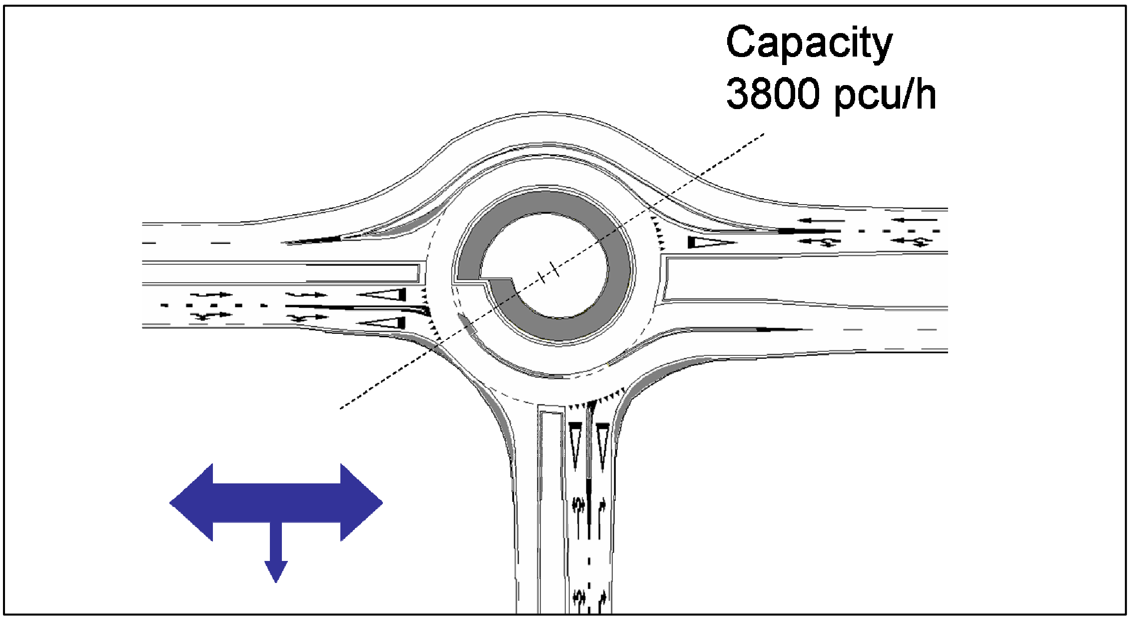


Figure 54: Stretched-knee roundabout

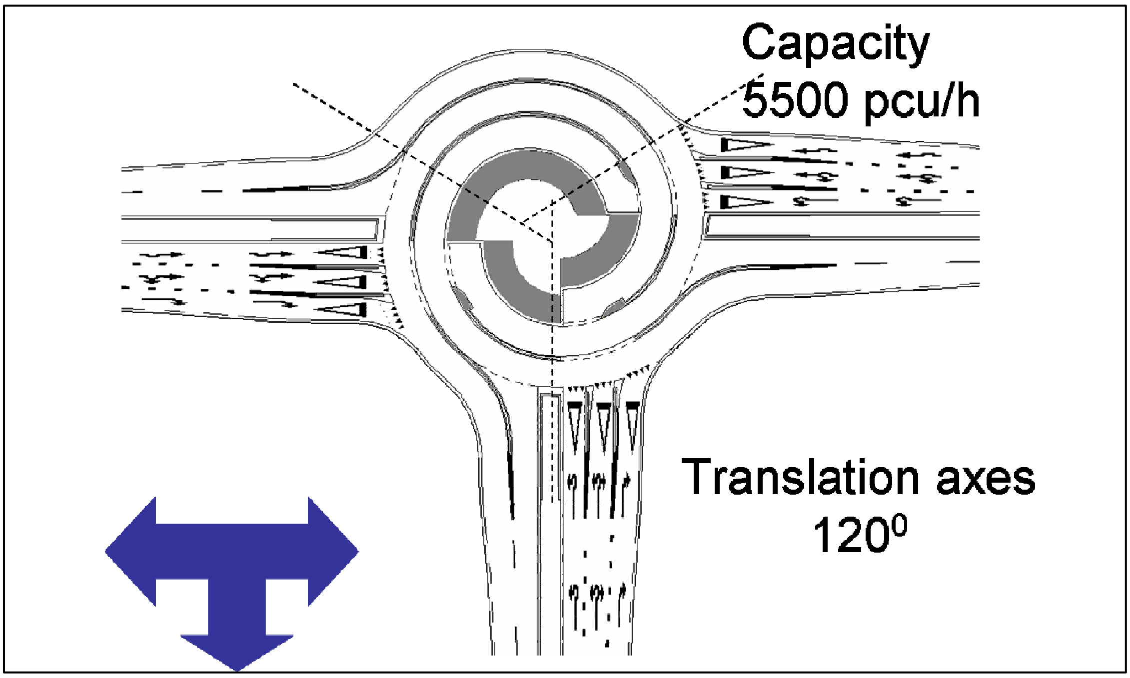


Figure 55: Star roundabout

Factors that determine the most suitable type are:

- saturation level;
- average delay time;
- spatial need;
- investment costs.

The province of Zuid-Holland in the Netherlands has developed a tool to compare the various types of turbo roundabouts, the ‘multi lane roundabout explorer’ (see section 3.3).

5.2.2 Design elements

Figure 56 illustrates the chief design features of a turbo roundabout. The features on the left are essential for a turbo roundabout; the features on the right are similar to those of a well-designed single lane roundabout (chapter 4).

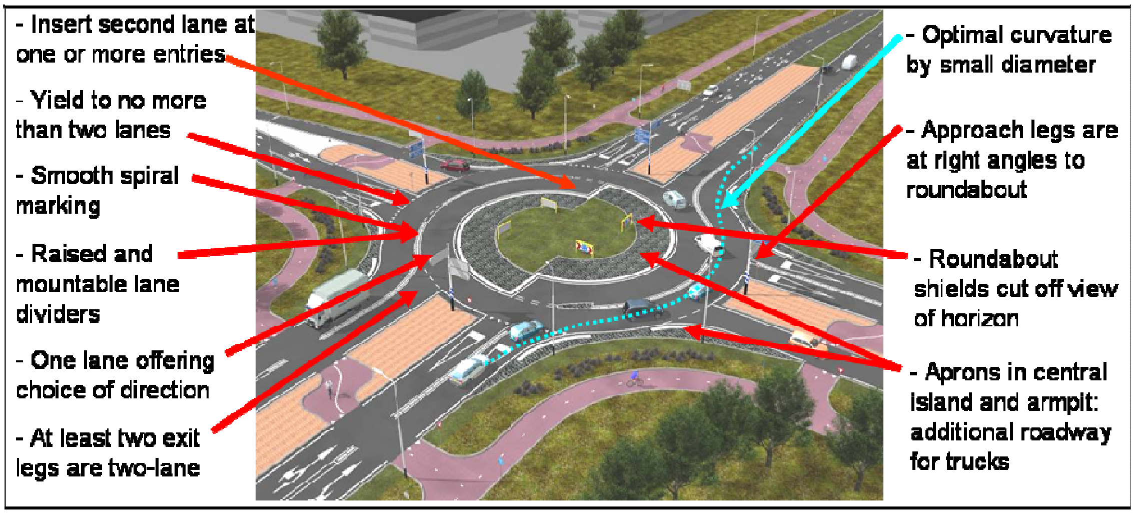


Figure 56: Design features of a turbo roundabout

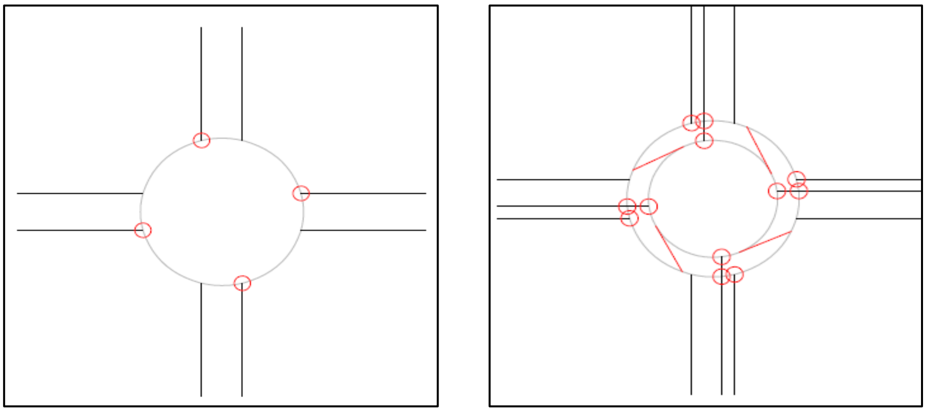
Essential design features

A number of design features can be called ‘essential’ in the sense that without these elements the intersection is not a turbo roundabout. These essential features of the turbo roundabout are:

1. opposite at least one entry a second lane in inserted on the central island side;
2. at least two entry legs (one leg at a three-leg roundabout) give way to traffic on two but no more than two lanes;
3. spiral marking fluently guide traffic from inside to outside, avoiding weaving and cutting conflicts on the roundabout;
4. mountable-raised lane dividers causes optimal vehicle curvature by keeping vehicles in their lane and by using a small diameter;
5. at least two exit legs are two lane;
6. on every section there is a decision point at which traffic can choose to exit or continue on the roundabout.

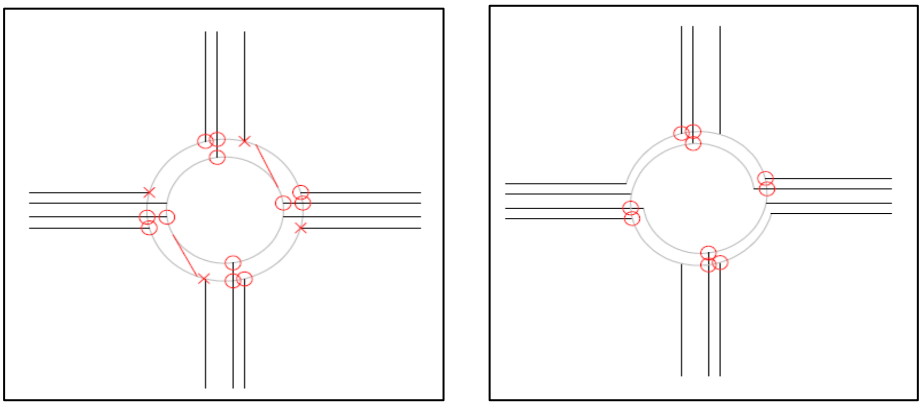
Conflict points

The overall road safety performance of an intersection is highly dependent on the number of conflict points. A turbo roundabout has fewer conflict points than multi lane roundabouts, but more than a single lane roundabout (see figure 57).



Single lane roundabout: 4 conflict points

Double lane roundabout, single lane exits: 16 conflict points;



Double lane roundabout, two lane exits: 20 conflict points

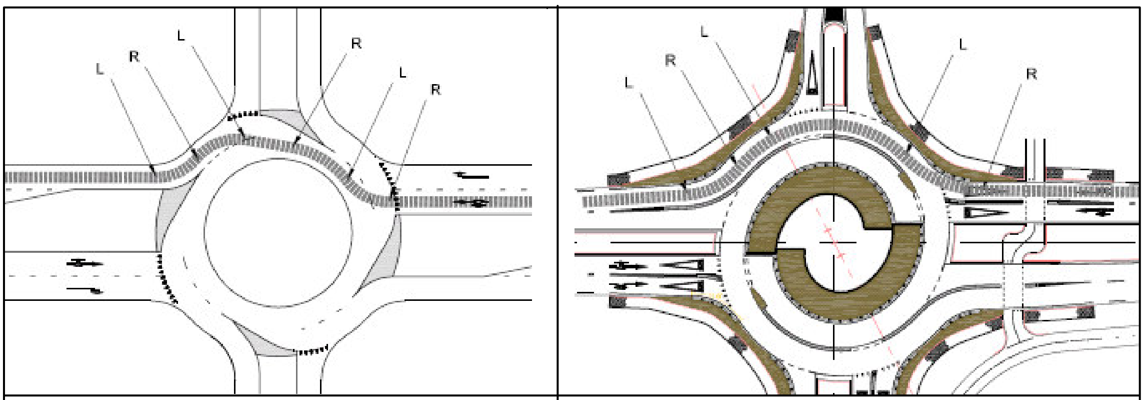
Turbo roundabout: 10 conflict points

Figure 57: Number of conflict points different types of roundabouts

Not only the number of conflict points, but also the type of conflict influences road safety performance. On turbo roundabouts there are no weaving and cut-off conflicts; instead, the conflicts all occur as vehicles enter the roundabout, where they have the opportunity to stop if necessary. Traffic behaviour is predictable, because vehicles keep to their lanes. Furthermore the lane dividers contribute to a low speed on the turbo roundabout.

Driving lanes

The connection of the approaching lanes should be as radial as possible. Because of the shape of a turbo roundabout and the principle of staying in your lane, drivers can pass through the roundabout in a fluent way. Compared to a concentric roundabout with spiral lanes, the driving path in a turbo roundabout requires fewer steering corrections to (see Figure 58)[4].

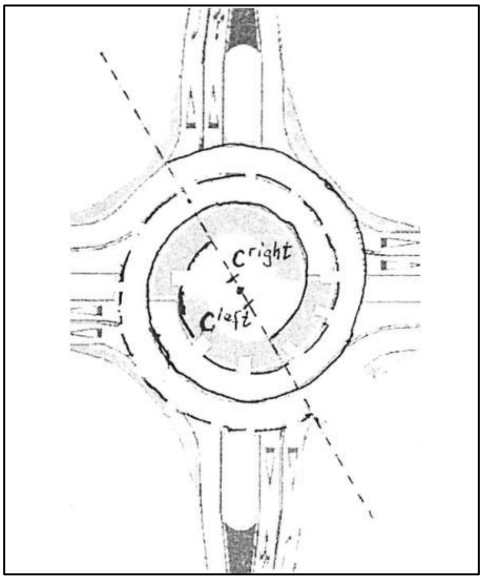


Concentric roundabout with spiral lanes **Turbo roundabout**

Figure 58: Steering corrections on roundabout with spiral markings and on turbo roundabout

Spirals

A turbo roundabout consists of spirals. These spirals are composed of segments of circular arcs, often semicircles, with each arc having a larger radius than the previous arc. When the radius of the arc changes, the centre of the arc changes by a corresponding amount so that the curve remains continuous.



In an idealized geometry, the basic turbo roundabout consists of two nested spirals, which represent lane boundaries. Each spiral consists of three semicircles with successively larger radii. The semicircles meet at a line called the translation axis. The arcs on the right side of the translation axis have a centre C^{right} that is above the overall centre of the roundabout; the arcs on the left side of the translation axis have a centre C^{left} that is below the overall centre. The distance between the centres of the arc segments is called the *shift* along the translation axis. The *bias* of an arc is the distance from its centre to the overall centre, and is therefore half the shift. In order for the spiral to be continuous, the shift must equal the change in radius.

Ideally, the shift is one roadway width, because the spiral moves out by one roadway width every 180 degrees. A sketch showing these spirals is called a 'turbo block', a useful design tool in the geometric design of a turbo roundabout.

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[4] R = right steering, L = left steering; the second L at the turbo roundabouts is still a left turning movement, but with a bigger radius. The driver has to make a slightly right steering correction.

Design process

The geometric design process has five steps. Step 1 is to select widths of the basic elements – the inner radius, the inside and outside roadways, the lane divider, and the offsets between the roadway edges and the lane lines. Figure 59 shows an example. Lane widths should be determined by analyzing the swept path of the design vehicle. Because swept paths are wider when the radius is tighter, the width of the inside lane (4.65 m measured line to line, or 5.30 m measured from pavement edge to divider) is 0.30 m greater than the width of the outside lane.

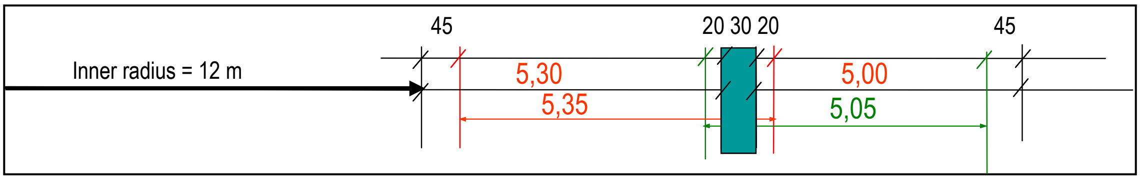


Figure 59: Lane, edge strip, and median strip widths and distances between edge lines in a turbo roundabout

Step 2 is to determine the shifts that the lane lines make, and the resulting biases for drawing the semicircular arcs. Unlike the ideal geometry, the actual geometry of a turbo roundabout's spirals is complicated by the need to account for different lane widths and for the width of the lane divider. Instead of a single centre point C^{right} for the semicircular arcs on the right side of the translation axis, there are two right-side centre points, one with a slightly larger bias than the other. The centre point with the larger bias is used for the innermost semicircle, to make the transition from inside edge to the middle divider; the other centre point is used for the remainder of the spiral. These two centre points can be seen in the turbo block sketch (see figure 60 and 61) of the example. Likewise, the arcs on the left side of the translation axis have two centre's with slightly different biases.

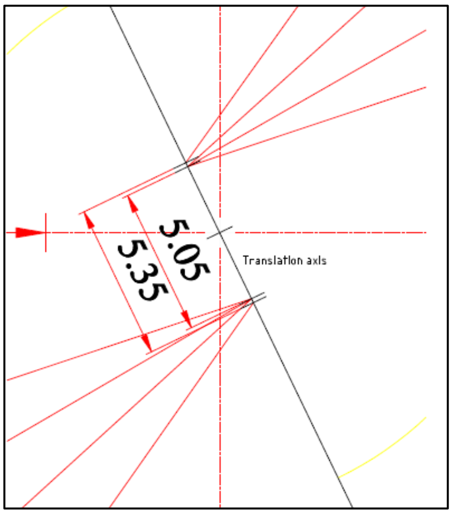


Figure 60: Detail showing centres for the arcs in a turbo roundabout

Shifts can be calculated from a cross section sketch such as in figure 59. There, one can see that the inner lane lines shift 5,35 m when transitioning from the inside of the roundabout to the lane divider. One can also see that the outer lane lines shift 5,05 m as they transition from the lane divider to the outside of the roundabout.

Step 3 is to calculate the radii of the circular arcs, and to sketch the turbo block. Depending on the need, one can focus on spirals representing lane lines, whose arcs have radii R1' to R4', or spirals whose arcs represent the roadway edges, with radii R1 to R4. Table 15 shows how these radii are defined and calculated.

Table 15: Turbo roundabout geometry calculations

Cross section elements	width				
inner radius	12.00				
inner edge line offset	0.45				
inside lane	4.65				
divider inner line offset	0.20				
divider (divider)	0.30				
divider outer line offset	0.20				
outside lane	4.35				
outer edge line offset	0.45				
Roadway widths, shifts, and biases					
inside roadway width		5.30			
outsider roadway width		5.00			
shift1 (inside to middle)			5.35		
shift2 (middle to outside)				5.05	
bias1 = shift1 / 2 (applies to R1 and R1')			2.675		
bias2 = shift2 / 2 (applies to all other radii)				2.525	
bias difference				0.15	
Radii for lane lines	arc centre bias	radius	start position	end position	'position' is relative to overall centre. start position = radius - bias; end position = radius + bias
R1' = inside lane, inner line	2.675	12.45	9.775	15.125	R1' = inner radius + inner edge line offset
R3' = outside lane, inner line	2.525	17.65	15.125	20.175	R3' = R1' + shift1 - bias difference
difference			*5.350*	*5.050*	*differences match shift1 and shift2; also, end position of R1' matches start position of R3'.*
R2' = inside lane, outer line	2.525	16.95			R2' = R3' - width of divider and divider offsets
R4' = outside lane, outer line	2.525	22.00			R4' = R2' + shift2 = R3' + outside lane width
Radii for roadway edges	arc centre bias	radius	start position	end position	start position = radius - bias; end position = radius + bias
R1 = inside roadway, inner edge	2.675	12.00	9.325	14.675	R1 = inner radius
R2 = inside roadway, outer edge	2.525	17.15	14.625	19.675	R2 = R1 + inside roadway width - bias difference
difference			*5.300*	*5.000*	*differences match roadway widths*
R3 = outside roadway, inner edge	2.525	17.45			R3 = R2 + divider width
R4 = outside roadway, outer edge	2.525	22.45			R4 = R3 + outside roadway width

The fourth step is the global rotation and translation of the turbo block to match the entering legs. Figure 60 shows the right position of the translation axis when the main stream is east-west. For a correct positioning of the translation axis, the distance between the right edge of each entry leg and the inner curve of the outer lane of the roundabout after ¼ turn should be more or less equal (A equals B, see figure 62).

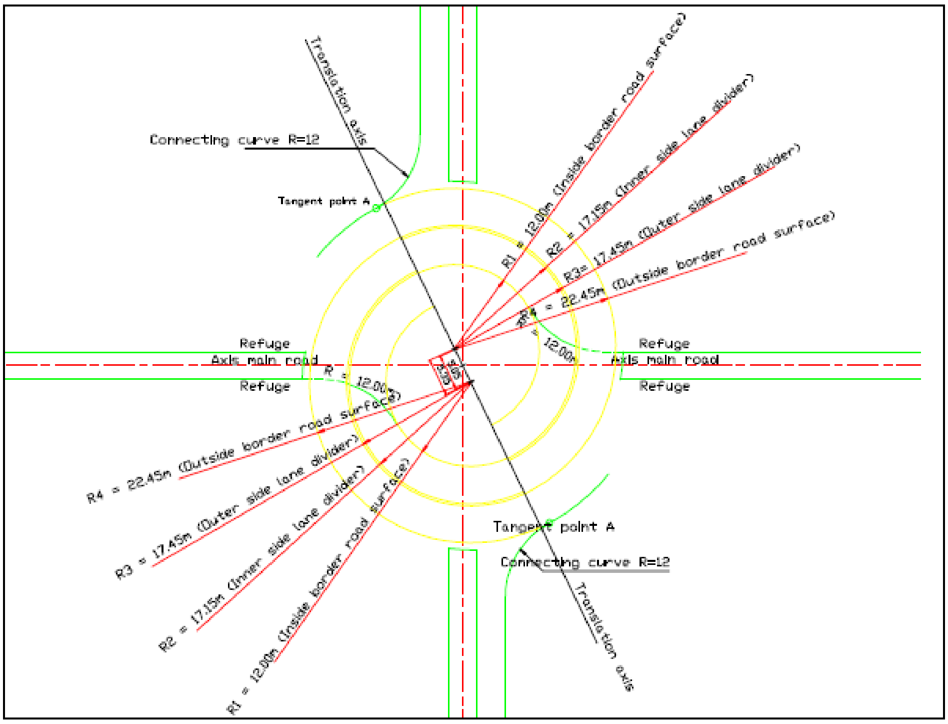


Figure 61: Turbo block of a standard turbo roundabout adjusted to the entries when the main traffic flow is east-west

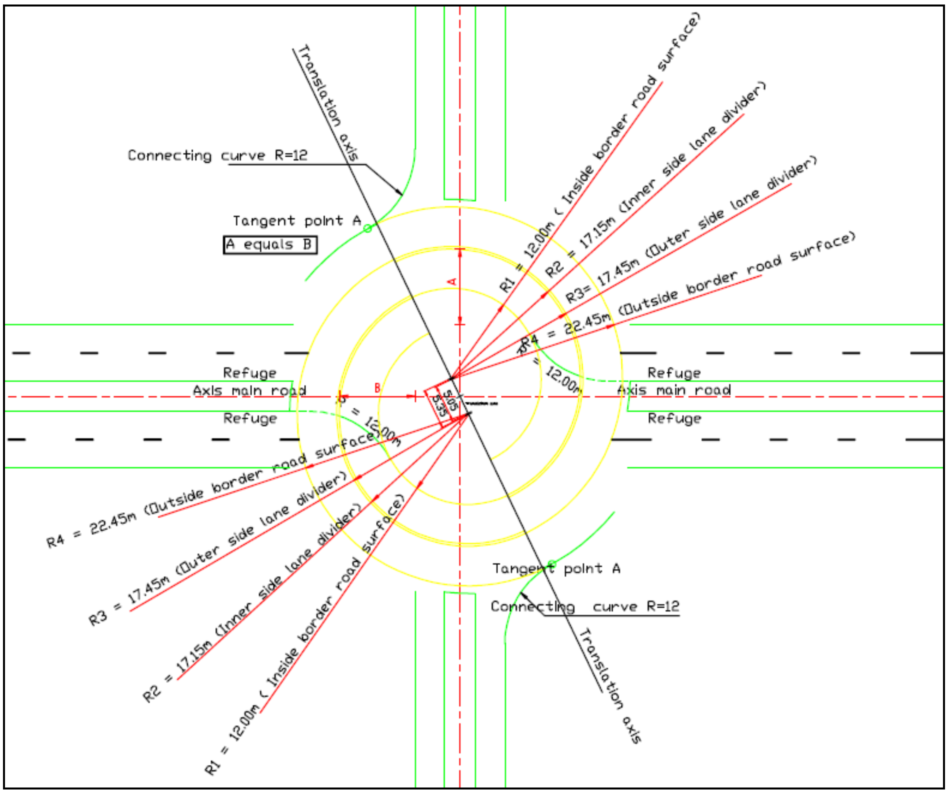


Figure 62: Checking positioning of the translation axis and overall centre

The fifth step is 'fine tuning' the position of the translation axis: tangent point A, where the inner curve of the entrance lanes connects to the outer curve of the roundabout's outer lane, should be positioned after the translation axis.

Design of other types of turbo roundabouts

The design process just described for the basic turbo roundabout is also valid for the egg roundabout, which also has two circulating lanes drawn from two nested spirals. Other roundabout types have different spiral patterns, and therefore require modifications to the geometric design.

A spiral roundabout has a similar geometry to the basic turbo roundabout, based on two nested spirals. However, its spirals have an additional semicircle in order to create a third circulating lane. Figure 63 shows an example of a cross section for a spiral roundabout.

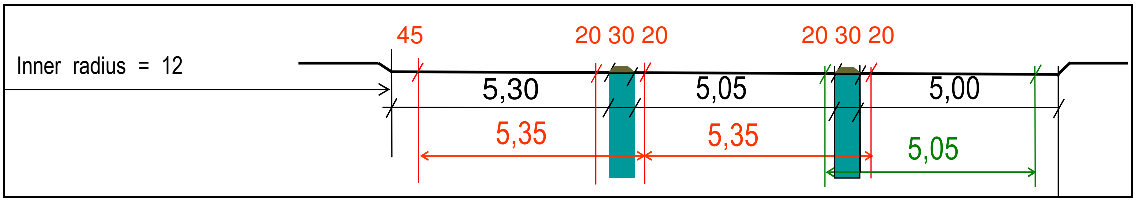


Figure 63: Lane width and distances between edge lines for a spiral roundabout

Because the shift in lane lines is 5.35 m for the transition from the inside to the first divider and from the first divider to the second divider, arcs corresponding to the inside of the roundabout and the first divider (radii R1, R2 and R3, as well as R1', R2' and R3') are drawn from a centre with bias equal to 5.35/2; the remaining, outer arcs are drawn from a centre with smaller bias 5.05/2. Calculation of the arc radii follows a similar logic to that used for the basic turbo roundabout.

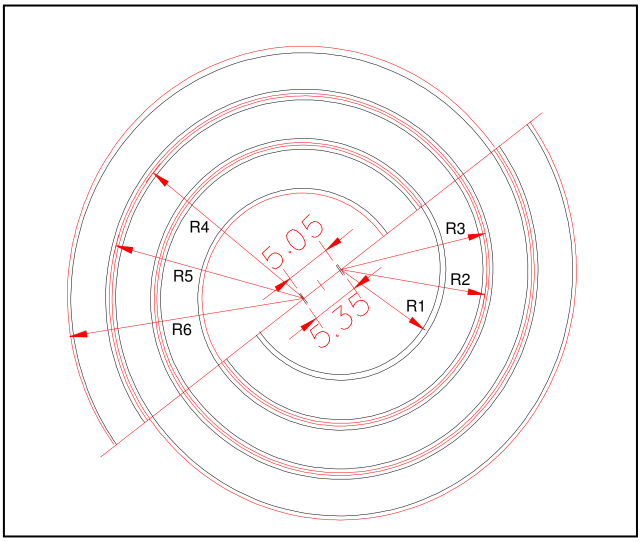


Figure 64: Turbo block detail for a spiral roundabout

The knee and stretched knee roundabouts (see figure 51 and figure 54) are based on a single spiral, rather than two nested spirals. Also, its spiral shifts only half of a roadway width with each semicircle. Therefore they have a simpler turbo block, with a single spiral whose, arc centres shift half the shift of the turbo roundabout.

The rotor roundabout (see figure 53) consists of four nested spirals; therefore, its turbo block has four translation axes (figure 65). For the star roundabout (see figure 55), which consists of three nested spirals, the turbo block has three translation axes. (figure 66).

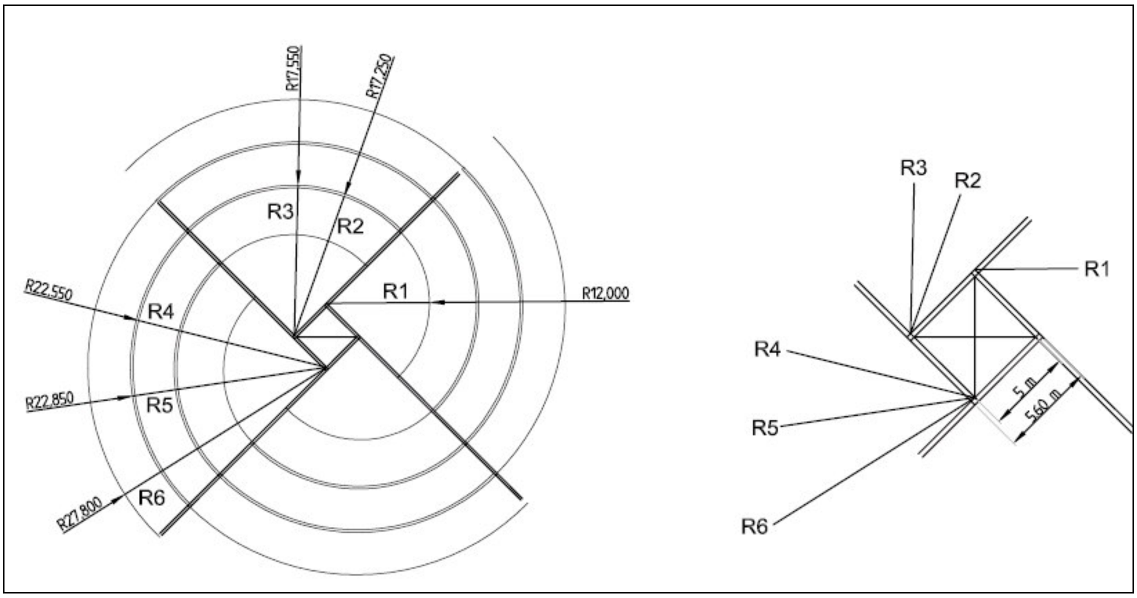


Figure 65: Turbo block for a rotor roundabout

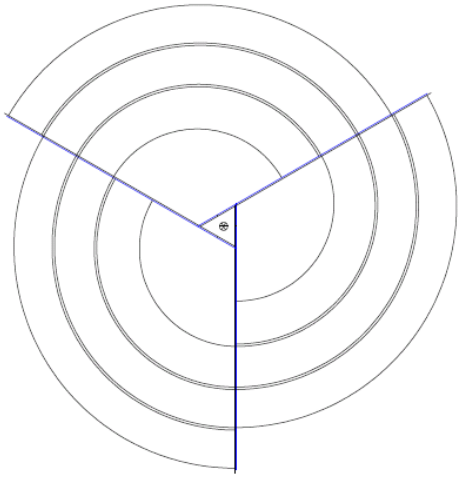


Figure 66: Turbo block for a star roundabout

Key parameters

The key parameters that determine the performance of a turbo roundabout are the radii for the different circular arcs and the lane widths. They are all related to each other. According to experiences in the Netherlands, the speed on the roundabout is the lowest when the radius of the inner curve of the inner lane is about 12 m. Because low speed is the most important goal for safety, in the Netherlands the standard dimensions are based on a radius of 12 m for the inner edge of the inside lane (see table 16).

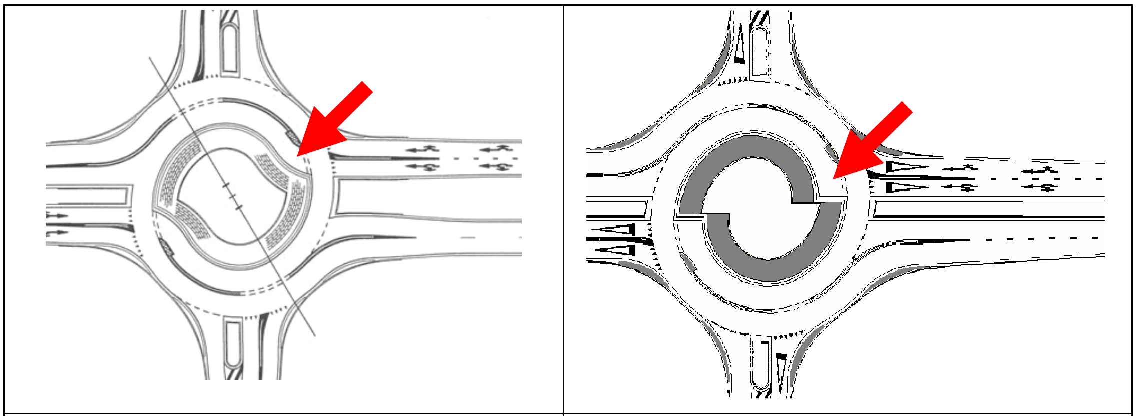
Table 16: Design elements of turbo roundabouts [5]

Feature		***Radius and measurement (m)***			
R_{inside} of the inner lane (all designs)	**R1**	10.5	12	15	20
$R_{Outside}$ of the inside roadway (all designs)	**R2**	15.85	17.15	20.00	24.90
R_{Inside} of the outside roadway (turbo-egg-spiral)	**R3**	16.15	17.45	20.30	25.20
$R_{outside}$ of the outside roadway (turbo-egg-spiral)	**R4**	21.15	22.45	25.20	29.90
Width, inside roadway		5.35	5.15	5.00	4.90
Width, outside roadway		5.00	5.00	4.90	4.70
Width, inside lane		4.70	4.50	4.35	4.25
Width, outside lane		4.35	4.35	4.25	4.05
Lane divider between driving lanes		0.30	0.30	0.30	0.30
Shift of inner arc centres along the translation-axis		5.75	5.35	5.15	5.15
Shift of outer arc centres along the translation-axis		5.05	5.05	4.95	4.75
Largest diameter		47.35	49.95	55.35	64.55
Smallest diameter		42.60	45.18	50.64	59.99
R, Curve entry and exit		10.00	10.00	10.00	10.00
R, Curve lane divider entry		12.00	12.00	12.00	12.00
R, Curve lane divider exit		15.00	15.00	15.00	15.00
Width, overrun area for vehicles with length 22 to 27m		5.00	5.00	5.00	max. 5.00
Speed, passenger car (km/h]		37-41	37-39	38-39	40

The key parameters for egg, knee and spiral roundabouts are the same as for the basic turbo roundabout. For key parameters of rotor and star roundabouts, see Appendix 2.

Start of the inner lane

In the past, the start of the inner lanes of turbo roundabouts were designed with smooth curves, in order to provide the approaching traffic from the left entry lane with guidance that matched the vehicle path (see figure 67). However, sometimes this approach caused confusion, as drivers entering the roundabout in the right entry lane mistakenly expected continuing traffic on the roundabout to shift into the inner lane. Therefore, as shown in figure 67, nowadays the preferred design is for the inner lane to start abruptly.



Old design for starting the inner lane **New design for starting the inner lane**

Figure 67: Old and new designs for starting the inner lane

Lane divider

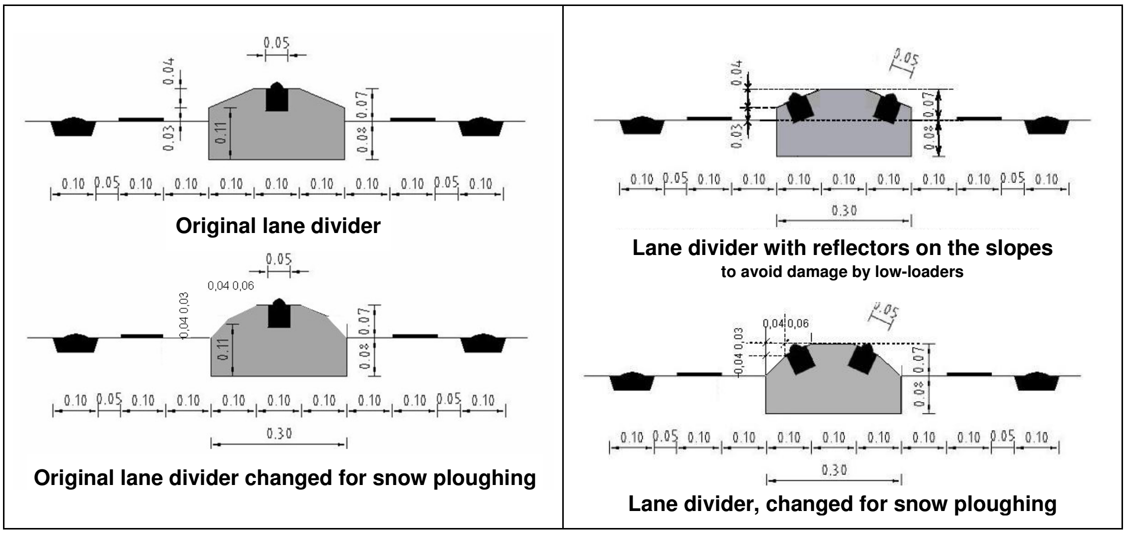
For the desired performance of a turbo roundabout, lane dividers are essential. The lane divider has four functions:

- prevents weaving and cut-off conflicts;
- prevents vehicles from straightening curves during low traffic periods;
- reduces fear of vehicles in other lanes;
- higher capacity due to lower speed (smaller critical gap for entering vehicles).

The lane dividers have to be elevated, strongly founded and introduced by a negotiable element, the so called ‘frog’, slightly wider then the lane divider. This ‘frog’ increases the visibility of the lane divider and protects against cutting the curve by passenger cars.

Figure 68: Examples of lane dividers

The design of different types of lane dividers can be altered to specific needs. In the example in figure 69 (on the left) the original lane divider is adapted for the use of snow ploughing machines on roads. The difference of the changed design from the original is a seamless connection between the road and the lane divider. Figure 69 shows also a lane divider adapted to avoid damage by low-loaders.



Original lane divider

Original lane divider changed for snow ploughing

Lane divider with reflectors on the slopes
to avoid damage by low-loaders

Lane divider, changed for snow ploughing

Figure 69: Types of lane dividers

5.2.3 Road marking, signposting and public lighting

Road marking

For the right use of a turbo roundabout it is important that road users are clearly informed before reaching the roundabout about the lane they have to choose in order to proceed in the desired direction. On turbo roundabouts driving a full circle to correct a wrong choice for the direction is not possible (unlike on conventional roundabouts). In addition to signposting, markings that mimic the information carried on signs are recommended. Figure 70 shows the different arrows used in the Netherlands.

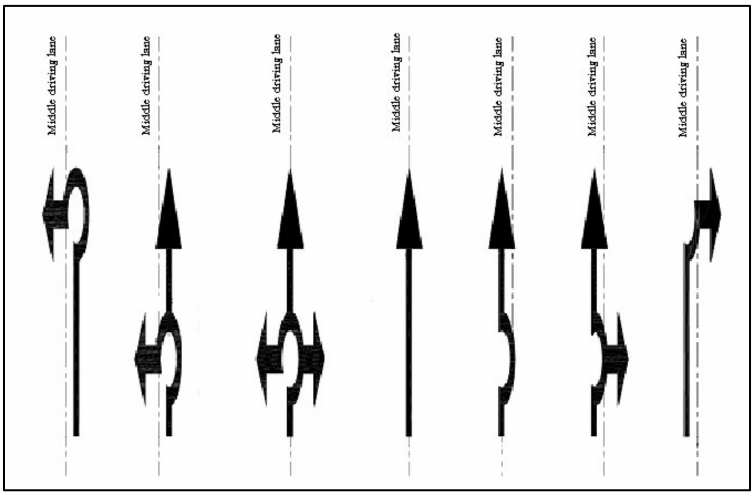


Figure 70: Arrows used on entry lanes, ahead of the roundabout

Arrows are used only on the entry lanes. Within the roundabout itself arrows are not repeated, because they do not provide the road user with additional, useful information.

Signposting

Because drivers need to choose the correct lane before entering the roundabout, clear signposting is very important. The first sign has to be posted at least 400 m ahead of the roundabout. At about 40 m ahead of the roundabout signs have to be placed either at the verge or above the traffic lanes, with the information stated per lane. It is important that the configuration of the arrows on the sign(s) is the same as the configuration used on the pavement (marking). Figure 71 shows examples of signposting ahead of the turbo roundabout. In order to guide the final decision on the roundabout itself, destinations are also signposted at the splitter island of the connecting road (see figure 72).

Figure 71: Signposting at 400 meters ahead of the roundabout

Figure 72: Signposting at the splitter island and traffic sign on the central island

Traffic signs

The turbo roundabout also demands a specific configuration of traffic signs. On the middle island there should be no hard elements, due to passive safety. Only the roundabout traffic sign is needed to block approaching drivers' view across the roundabout (see figure 72). The sign should be made 'collision friendly'.

Road users on turbo roundabouts have to receive and interpret much information. Therefore it is important to design markings, signposting and traffic signs as one concept, in order not to overload the road user with information. Be sure that the road user is clearly informed in plenty of time using a minimum of signs. After leaving the turbo roundabout, drivers need time to recover and pay renewed attention. Therefore there should be a distance of at least 200 m between the exit of a turbo roundabout and the first signposting of a next intersection.

Public lighting

The aim of public lighting on turbo roundabouts is drivers. Of course the visibility of the intersection and the alignment of the lanes have to be assured. Specifically for turbo roundabouts, public lighting should be used to improve visibility of the middle island and the lane dividers (see figure 73). It can also be used to pay extra attention to conflict points or specific elements of the turbo roundabout.

Figure 73: Example of road lightning (LED) to improve visibility of the lane dividers

5.2.4 Special user groups

Pedestrians and cyclists

As on multi lane roundabouts, pedestrians and cyclists should not use a turbo roundabout (see section 5.1.4), but should be provided with an alternative route.

Powered two wheelers

Lane dividers create a risk for powered two wheelers, which can easily fall when driving over a lane divider. Nevertheless, experience in the Netherlands shows that motor cyclists prefer turbo roundabouts to a multi lane roundabouts, because they do not have to fear cars changing lanes on the roundabout. For the safety of the motor cyclists it is essential to put clear signs to warn them about the lane dividers (see figure 74; 'verhoogde rijbaanscheiding' = raised lane-divider).

Figure 74: Warning sign 'raised lane dividers' for motor cyclists

Figure 75: Rumble area for articulated vehicles

Public transport

Adding special lanes for public transport on a turbo roundabout is more difficult than on a multi lane roundabout (except for right turning public transport). For road safety reasons (unexpected conflict points) it is not recommended.

Exceptional transport

Exceptional transport can make use of the rumble area (see figure 75) that also provides normal trucks with manoeuvring space, without over dimensioning of the road surface, leading to (too) high speed of passenger cars. Another possibility is to add special features, which can be especially useful when exceptional transport takes place in a particular direction (see figure 76).

Figure 76: Exceptional transport guided by a traffic organizer

6 SIGNALIZED ROUNDABOUTS

Sometimes neither a single lane roundabout, multilane roundabout, turbo roundabout, nor signalized priority intersection can cope with the volumes of the different traffic flows at an intersection. In these cases a signalized multilane roundabout might be a satisfying alternative to an expensive and space consuming grade separated intersection.

A signalized roundabout is a multilane roundabout in which the traffic signals control the traffic. Traffic signals are generally added to a roundabout in order to solve specific problems, mainly related to capacity or quality of traffic flow. The most important reasons are:

- insufficient overall capacity of the roundabout;
- heavy left turning traffic flow;
- unacceptable delays and/or queues on one or more of the connecting legs.

Sometimes the problems to solve are (also) traffic safety related:

- due to high circulating speeds drivers experience difficulties when merging with the traffic on the multilane roundabout;
- for pedestrians and cyclists it is difficult to cross multilane legs of the roundabout.

Little is known about the performance of signalized roundabouts, both related to traffic flow and to traffic safety, although many have been built with different sizes and shapes. This chapter presents the main characteristics of four types of signalized roundabouts and provides a step by step approach for the design of a signalized roundabout.

6.1 Types and characteristics

The various existing signalized roundabouts can be functionally divided into four categories:

1. traffic signals meter traffic on one or more entries;
2. traffic signals control entries and exits for the benefit of crossing pedestrians and cyclists;
3. traffic signals control both the entries and the circulating lanes;
4. traffic signals on a turbo roundabout.

These four categories focus on different goals and have different characteristics. They are briefly described hereafter. The final design usually depends on three general aspects:

- volume of traffic flows per direction;
- overall safety performance;
- availability of space.

1. Metering traffic on one or more entries

If the entering and circulating volumes on a roundabout are not evenly spread, lengthy delays can occur on one or more legs. This event occurs typically during peak hours on roundabouts in urban areas. In those situations traffic flows often have strong directional characteristics [23].

The system of metering principally works as follows. Queues at the entries of a roundabout are monitored. When one of the queues exceeds a preset critical length, a red traffic signal will appear at the entry of the dominant conflicting flow of the circulating traffic. The resulting extra gaps in the circulating traffic flow on the roundabout will be used by the traffic on the delayed entry.

Metering signals have the normal three colours. Similar signals have been applied on motorway entry ramps in the Netherlands to meter entering traffic flow (see figure 77).

Figure 77: Entry signals on entry ramp of motorway

Metering does not increase the overall capacity of the roundabout. It only redistributes the time in favour of the delayed flow at the expense of a conflicting flow. Research in Australia showed that on single lane roundabouts the system is only useful when the combined volumes of the traffic flow on the delayed entry and the circulating traffic exceeds about 1300-1400 vehicles per hour. The benefits begin to decline once the combined volume is between 1550 and 1650 vehicles per hour [23].

Metering signals are typically added to existing (single lane) roundabouts; an overall redesign of the roundabout is not necessary. Metering signals have only limited use for increasing capacity. Where there is a capacity shortage, it will usually be preferable to change the layout of the roundabout (extra lanes, bypasses, or turbo-roundabout). Other alternatives are a normal signalized intersection (not necessarily leading to better performance) or a grade separated intersection.

2. Traffic signals on multilane entries and exits for crossing pedestrians and cyclists

For pedestrians and cyclists it is not easy to cross multilane entries and exits of roundabouts. Adding traffic signals on both the entries and the exits may help to ease this. Pedestrians and cyclists should be routed away from self-regulating multi lane roundabouts (see section 5.1.4). Nevertheless this may not be possible in all cases, especially within built up areas. As this manual focuses on roundabouts outside built up areas, the use of traffic signals for this function is not explored in more detail.

3. Traffic signals on both the entries and the circulating carriageway

To fully control the traffic in a roundabout, traffic signals must be placed on all entries and on the circulating lane(s) in front of the entries. By doing so, time can be distributed optimally to the different traffic flows per direction, see figures 78 - 80.

The traffic signals may result in an increase of the overall capacity, but capacity will drop rapidly if a queue on the circulating lanes blocks an upstream exit or entry. This event can easily occur if there is too short a buffer on the roundabout. Therefore the distance between the exit and entry serving the same leg needs to be sufficient. Alternatively or additionally, the number of lanes on the circle has to be increased. Therefore a useful multilane roundabout with traffic signals on both the entries and the circulating roadway needs to be quite large in order to have enough space to buffer queues on the roundabout.

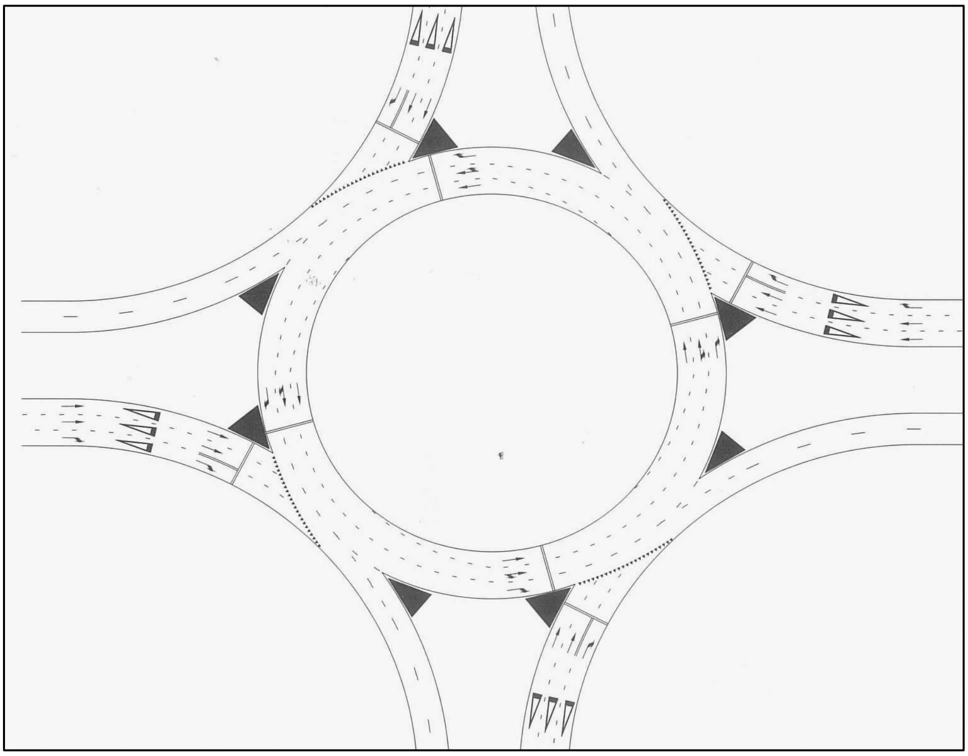


Figure 78: Principle of signalized multi lane roundabout

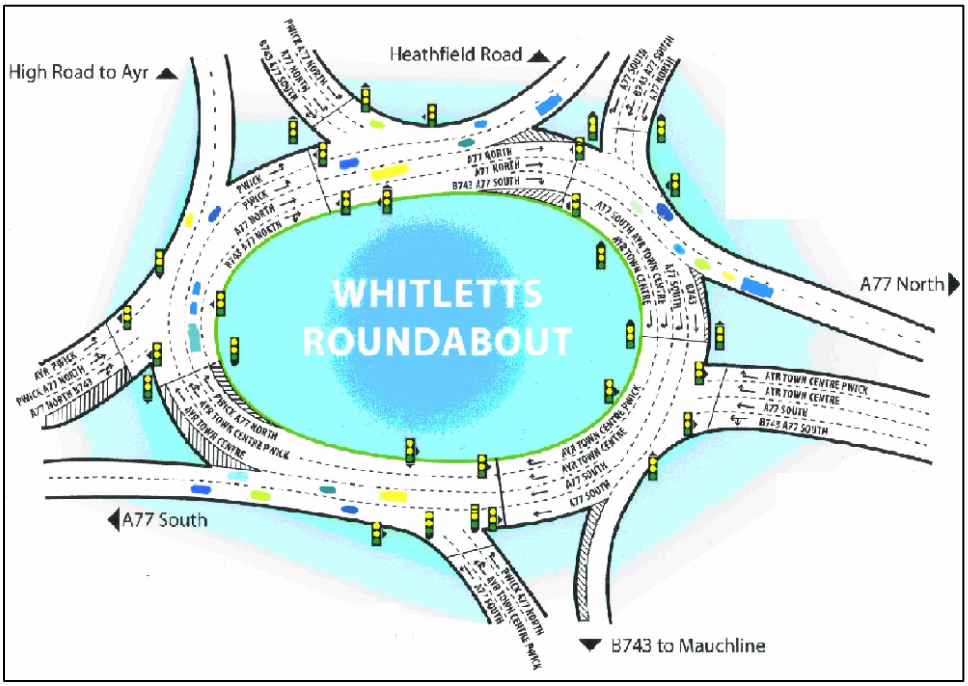


Figure 79: Signalized multi lane roundabout with spiral marking (Whitletts, UK)

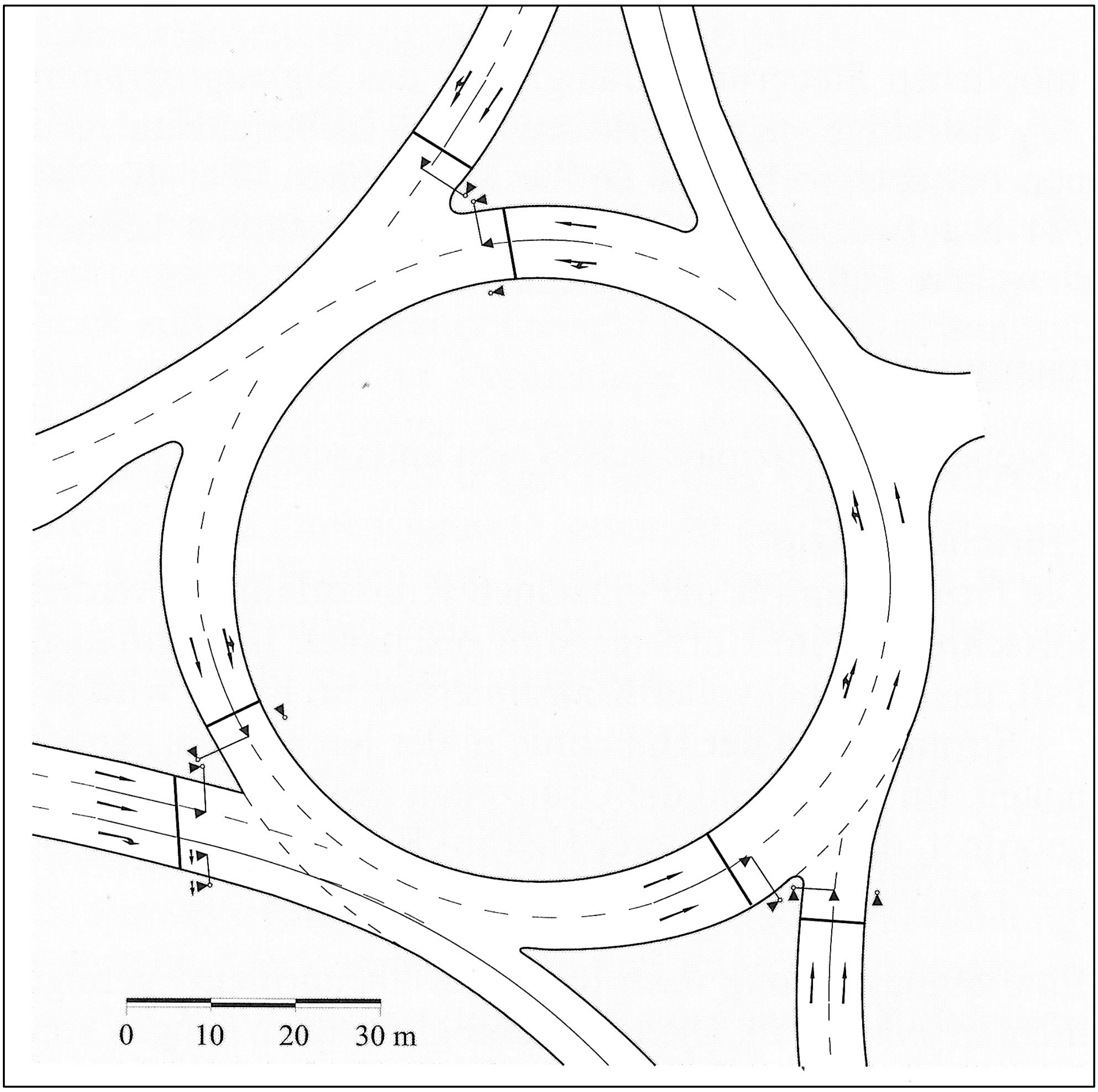


Figure 80: Signalized multi lane roundabout in Germany [13]

A signalized roundabout preferably has a two phase control (see figure 81), timed to provide alternating green waves for east-west and for north-south through traffic. With two-phase control, through going traffic may be stopped before it enters the roundabout, but should not have to stop on the circulating roadway. However, left turning traffic will be stopped on the circulating roadway, and so enough buffering space has to be available for left turning traffic. If the volume of left turning traffic is relatively high, this might easily lead to queues blocking through going traffic from exiting the roundabout, sharply reducing overall capacity.

Where left turn movements are heavy, four phase control can be used, with the traffic signals on the entries showing green in succession clockwise. However, while this scheme maximizes capacity for left turn movements, it limits capacity overall because time-space 'reserved' for left turn flows goes unused to the degree that there is through traffic.

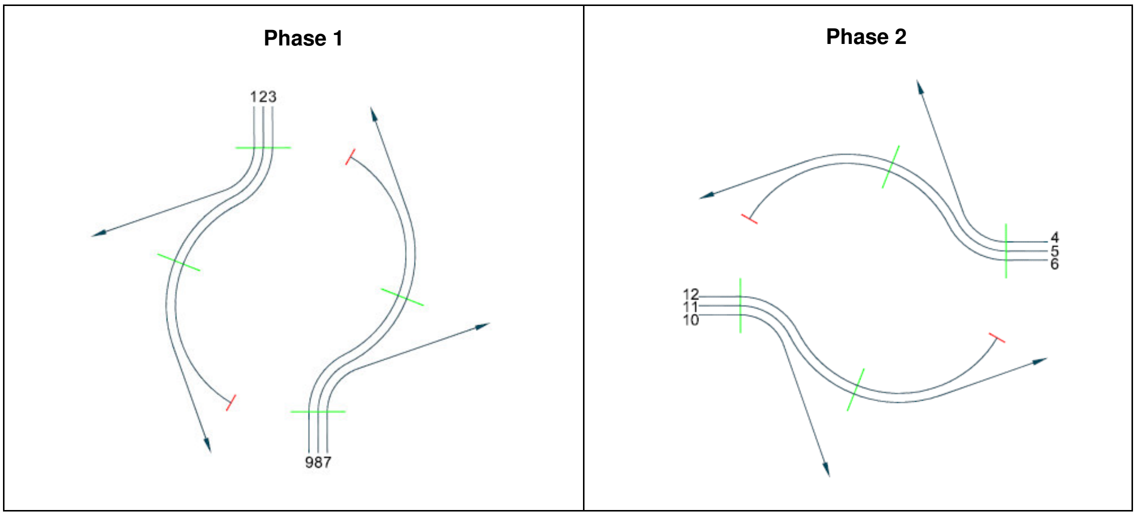


Figure 81: Two-phase traffic control

4. Turbo roundabout with traffic signals

The turbo roundabout with traffic signals is a new development in the Netherlands. It seeks to combine the safety advantages of a turbo roundabout with traffic flow advantages of traffic signals. The basic design of a turbo roundabout with traffic signals is based on the rotor roundabout. One of the main characteristics of a turbo roundabout with traffic signals is the fact that each traffic direction has its own separate lane or lanes. There are no combined lanes to be used by traffic exiting the roundabout at different exits (see figure 82). This implies that traffic signals cannot just be added to an existing turbo roundabout; the roundabout has to be redesigned.

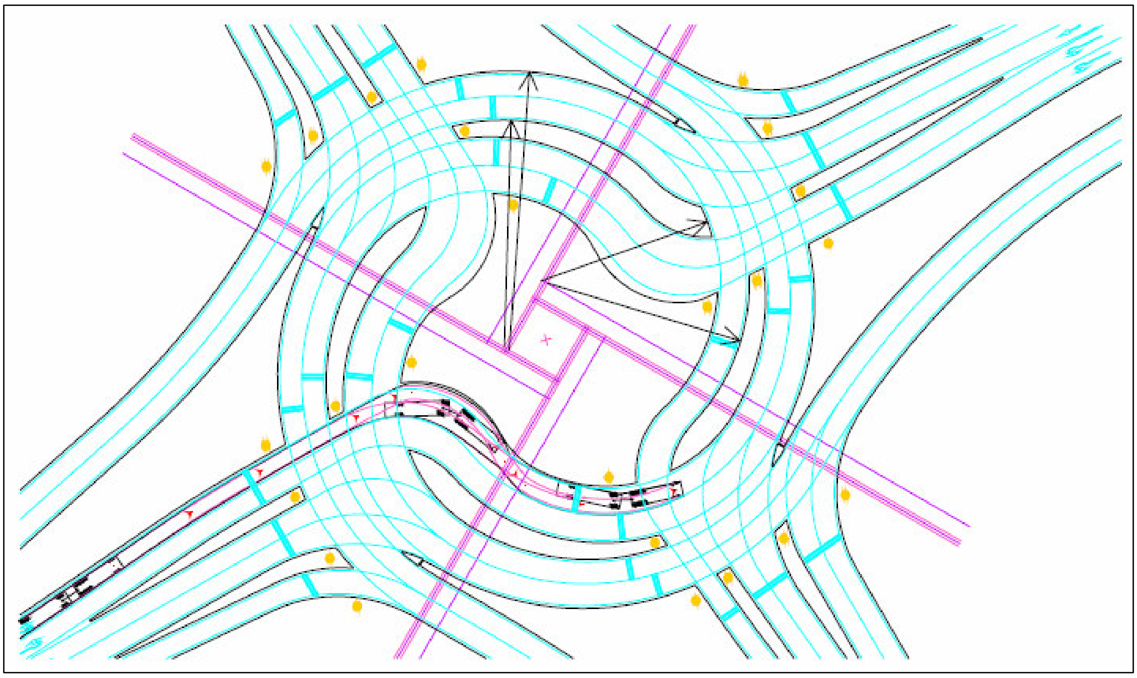


Figure 82: Concept design of a signalized turbo roundabout

In this design concept, the buffer length for left turning traffic is half of the roundabout, which is far greater than with a traditional multi lane roundabout (see figure 83).

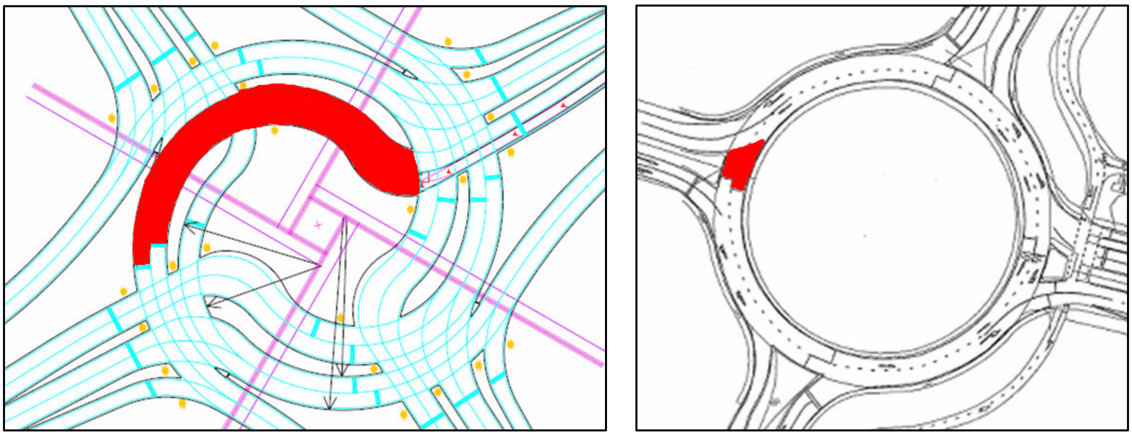


Figure 83: Buffer for left turning traffic: turbo roundabout versus multi lane roundabout

In order to clear the circulating road before another traffic flow enters the roundabout, the traffic signals on the roundabout have to switch green earlier than the traffic signal on the entry. The number of lanes on a signalized turbo roundabout per direction depends on the volumes.

Signalized turbo roundabouts are designed according to the same principles as normal turbo roundabouts. However there are some differences:

– to create a buffer the distance between the entry and exit point is as large as possible. This allows a fast two phase control with short cycle times;

– every direction has its own separate lane, contrary to a normal turbo roundabout where at least one lane offers a choice between two directions;

– the diameter of the signalized turbo roundabout is 120 – 130 m.

The connection between the exit leg and the roundabout is tangential. This increases the queuing space on the roundabout. The main characteristics of a signalized turbo roundabout are listed in the table below.

Table 17: Characteristics of a signalized turbo roundabout

Name	**General signalized turbo roundabout**
Number of connecting legs	4
Volume	Approximately 11.000 – 12.000 veh/h
Priority	Traffic on the circulating roadway
Number of lanes, minimum	3, so that each direction has a separate lane
Number of lanes, maximum	3 per direction, due to safety (comprehensibility)
Size	diameter 120 -130 m
Location of traffic signals	on entries and on the circulating roadway
Marking of the lanes	spiral

As for all types of signalized roundabouts, currently there is no standard design for a signalized turbo roundabout. On signalized turbo roundabouts so far the lanes on the roundabout have a width of 8 m at the transition to a double lane exit. The inner lane is 10 m wide and reduces to 8 m towards the exit. The start of the inner lanes cuts through the central island. The space gained this way is used to create driving lanes with large widths. This allows large truck combinations to safely use all lanes simultaneously. There are islands between the directions of roughly 2.50 m width. All other measurements depend on local conditions. There are two signalized turbo roundabouts operating in the Netherlands at this moment (2009): Doenkadeplein (see figure 84) and Tolhekplein. An evaluation study was executed in 2007 [32].

Figure 84: Example of signalized turbo roundabout (Doenkadeplein, the Netherlands)

The main advantage of a signalized turbo roundabout in comparison with a normal turbo roundabout is the increase of capacity (both with a two-phase control). The table below shows a comparison. The capacities were found by simulation. Minor differences are not statistically significant. The main, significant difference is the left turning capacity.

Table 18: Conflict load at a turbo roundabout

	Without traffic signals (pcu/h)	With traffic signals (pcu/h)
Volume inner lane	727	752
Volume outer lane	532	536
Volume opposite direction (exit)	360	436
Capacity entering lane (left turning)	476	884

A disadvantage of signalized turbo roundabouts is the rather complicated layout, which some road users may not understand directly. There is a risk of road users using the infrastructure in a wrong way. For example, left turning traffic might want to turn left in front of the central island of the roundabout and use one of the lanes on the circulating roadway in the opposite direction. The roundabout is too large to oversee, so road users may not know what is expected of them. To prevent misunderstandings, much attention is necessary for clear signposting, clear indications on the traffic signals, and road markings.

The capacity of different types of junctions has been indicated in table 3 (section 3). Factors usually having a limiting influence on the capacity of roundabouts are pedestrians, cyclists, trucks, buses and features for giving priority to public transport.

6.2 Design process

There are no standard design parameters for signalized roundabouts. The designs of existing signalized roundabouts are mostly based on general road-design experience and common sense. In general the design should be based on the fact that drivers should be able to reach their desired destination in relatively safe circumstances. For the design of signalized roundabouts traffic micro simulation programs are used to optimize the design and the traffic control.

For the design of signalized roundabouts a number of steps should be taken into consideration. These steps are described in this paragraph, taking into account as starting points:
- the junction is located outside built-up area;
- pedestrians and cyclists do not use the junction;
- the capacity of a usual (turbo) roundabout is insufficient;
- metering signals are not a solution.

Traffic signals should only be added if adding extra lanes on an existing self-regulating (turbo) roundabout does not solve the problem or is not possible. As discussed before, metering signals might be a solution only in a small range of combined demand volumes (conflict load). Therefore metering signals are only useful when capacity is slightly insufficient and expected future traffic growth will be limited. In all other cases fully signalized roundabouts should be considered.

The design process of signalized turbo roundabouts consists of the following steps (see figure 85):
1. determine the traffic volume per direction;
2. examine whether a signalized roundabout is a suitable option;
3. determine the capacity of the roundabout;
4. test and optimize design and traffic regulation by micro simulation;
5. design markings, signposting and traffic signs.
6. consider alternative solutions in case a signalized turbo roundabout does not solve the problem.

Step 1: Determine traffic volume per direction
For the design of a signalized roundabout, the (forecasted) traffic volume per direction, especially for left turning flow, is of high importance. They help determine some of the main design parameters: the required number of lanes per direction, the required width of the islands between the entry and exit legs, and the required diameter of the roundabout. Also the traffic composition is important, because large vehicles such as trucks and buses influence the overall capacity of the roundabout.

Step 2: Examine whether a signalized roundabout is a suitable option
Signalized roundabouts need space. The diameter should be at least 100 meter. If this space is not available or cannot be made available, there is no use in considering this option. An alternative solution has to be found (go on to step 6).

A first rough estimation whether the capacity of a signalized roundabout will match the traffic volumes can be done by looking at table 3 in chapter 3. This estimation can be based on the theoretical capacity in the peak hour (veh/h) and the conflict load per direction (approaching traffic per entry + conflicting traffic on the circulating road in pcu/h). If the estimated traffic volume doesn't fit, an alternative solution has to be found (go on to step 6).

Step 3: Determine capacity of the roundabout
Capacity of the roundabout is determined by he overall geometric design, the number of lanes per direction and traffic control. Starting point of the design process is a roundabout with 4 entries and exits, at which a two-phase control is possible. At a signalized (not turbo) roundabout it is possible to add an extra leg, although it decreases the capacity significantly. In that case a two-phase control is not possible. This reduces the advantages of a signalized roundabout in comparison to a normal signalized junction.

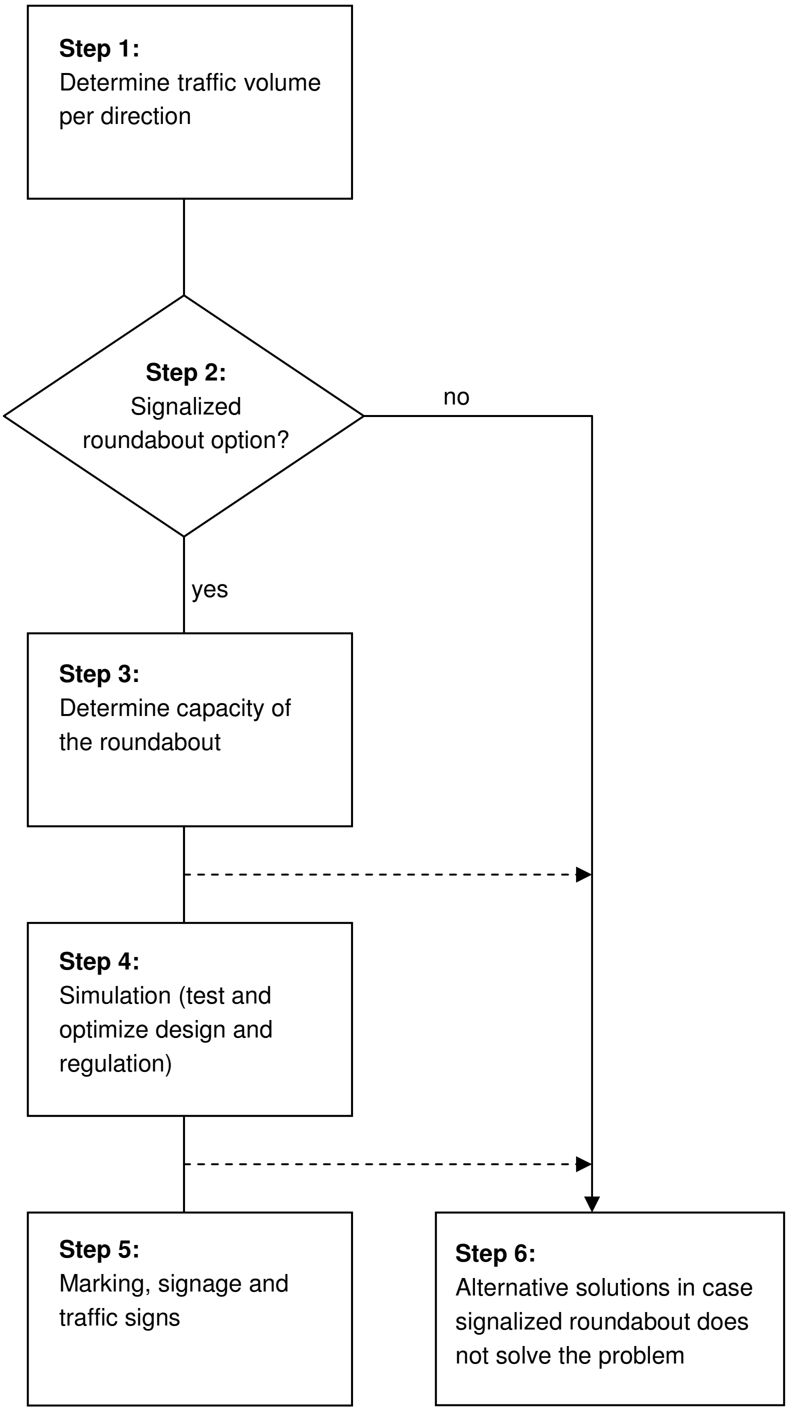


Figure 85: Design process of a signalized roundabout

As described earlier, an important advantage of a signalized roundabout with 4 legs is being able to use two-phase control: less clearance time, less delay and high capacity. But there are disadvantages as well:

- it might be necessary to shorten the green phase of a direction, because queues of left turning traffic in opposite directions can block another flow;
- traffic cannot enter the roundabout before the queue of left turning traffic has cleared the part of the circulating roadway in which it enters.

Consequently there has to be enough space for buffering left turning traffic on the circulating roadway. Furthermore the traffic signals on the circulating roadway have to switch green earlier than the traffic signals on the downstream entry.

The required number of lanes (both on entries and on the circulating roadway) can be determined per entry by calculating the conflict load. As a rule of thumb, the maximum conflict load of two conflicting traffic flows is approximately 1,500 pcu/h (including loss due to clearance time). The mutual influence between the different entries and the possible gridlock effect from opposing left turns are not taken into account yet. To calculate the necessary buffering space per direction a more precise calculating method has to be used. In the frame below a possible calculating method is briefly explained.

Left turning traffic might have to stop at the traffic signal on the roundabout. For this traffic flow there must be adequate buffering space on the circulating roadway. With two-phase control, that buffering space lies between the opposite leg's exit and entry. The necessary buffering space, measured in number of pcu's that can be queued, depends on the green time of the entry lane. Therefore the maximum green time per cycle for the signal that controls left turning traffic at an entry may not exceed the time that the buffering space (As2 [pcu]) permits.

For each left turning movement, the following formula can be applied:

$g < As2 / Q_{LT}$

g = maximum green time before the buffer is exceeded [s]
$As2$ = buffering space for left turning traffic on the circulating roadway [pcu]
Q_{LT} = left turning traffic volume at the entry [pcu/s]

A rule of thumb for a signalized turbo roundabout is that the green time of left turning traffic should not exceed 25 seconds; especially when two opposite left turning traffic flows have relatively high volumes. Another point of concern is the number and length of the lanes on the exits. Both the number of lanes and their lengths have to be great enough so that the exits do not influence the capacity of the roundabout.

Step 4: Simulation (test and optimize design and regulation)

Optimizing the traffic control program in conjunction with the layout of the roundabout is an iterative process. In order to reach an optimal solution, it is recommended to test the combination of the layout of the intersection and the traffic control program by micro simulation. For example, adapting the length of lanes on the entries can improve the design. Concerning the traffic control program, coordination between the traffic signals on the roundabout should be optimized in order to guarantee green light on the circulating roadway for through traffic. Traffic in this direction should not have to stop twice. Also, the green time in relation to the buffering space for left turning traffic on the circulating roadway can be optimized. An optimized traffic control program results in the highest capacity of the designed roundabout.

Step 5: Marking, signposting and traffic signs

Theoretically, signalized roundabouts can perform well in situations with high traffic volumes. Whether they perform as well as expected depends on the behaviour of the road users. Road users should be well aware of the shape of the intersection and the way the infrastructure should be used, according to the intent of the designer. The overall geometric design of a signalized turbo roundabout can be complex due to the many lanes needed per direction in order to cope with the high traffic volumes. Therefore the task of passing through the intersection should be simplified as much as possible for the road users. Marking, signposting and traffic signs are crucial to making the infrastructure understandable and easy to use.

First off all, signposting has to be very clear before entering the roundabout. Markings should correspond to the signs, especially at signalized turbo roundabouts, where road users have to choose the correct lane before entering the roundabout. See chapter 5 for some details.

Clear markings are also, needed on the circulating roadway in order to guide road users in the right direction. Because roundabouts already demand that users take in a lot of information, there should be as few signs as possible on the circulating roadway. Too many signs and too much additional information can confuse road users, which may have a significant negative influence on capacity and road safety.

Step 6: Alternative solutions in case signalized roundabout does not solve the problem

The result of this design process might be that a signalized roundabout is not a (sustainable) solution for the problem (number of lanes / diameter). In that case another solution has to be found. The main options are:

- grade-separated intersection;
- rearrange traffic flows (network measures);
- adding a new (by pass) road.

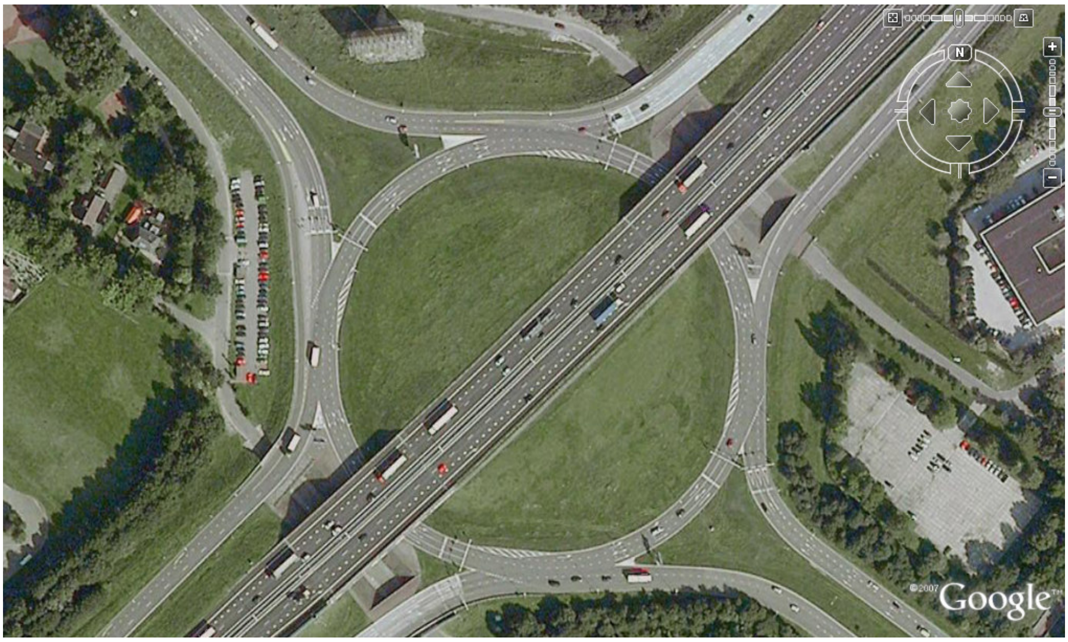


Figure 86: Signalized roundabout (the Netherlands)

7 EPILOGUE

In many countries, traffic engineers have studied how to solve safety problems and capacity restraints at intersections. In this manual a part of this knowledge has been collected. The manual shows how roundabouts can increase both safety and capacity of intersections by offering a number of standard options. Hopefully it provides some useful, practical guidance for professionals working in this field. However, the standard options in this manual should never be copied into practice without thoroughly considering the specific design aspects related to the country or the location itself.

In trying to create an optimal solution for a specific situation, traffic engineers sometimes come up with unusual designs. Often opinions differ over the success or failure of such unusual roundabouts. The user of this manual can judge for him or herself whether the designer of the 'magic' roundabout in Swindon [5]) (United Kingdom) succeeded.

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[5]) The magic roundabout in Swindon, halfway between London and Cardiff in the UK, is a very original way to accommodate different traffic flows at a 5-leg junction. This large roundabout contains 5 small roundabouts, which help traffic entering and exiting the roundabout. Traffic circulates around the large roundabout both clockwise and anticlockwise. The traffic signs are adapted for the magic roundabout.

8 COLOPHON

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APPENDIX 1 Literature sources

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APPENDIX 2 Main measurements for rotor - and star roundabouts

Rotor roundabout [4]

Characteristic	**Radius and measurements rotor roundabout (m)**			
R_{inside} of the inner lane	**R1**	**12**	**15**	**20**
$R_{Outside}$ of the inner lane	**R2**	17.25	20.15	24.95
R_{Inside} of the central lane	**R3**	17.55	20.45	25.25
$R_{outside}$ of the central lane	**R4**	22.55	25.35	29.95
R_{Inside} of the outer lane	**R5**	22.85	25.65	30.25
$R_{outside}$ of the outer lane	**R6**	27.80	30.50	34.90
Physical barrier between driving lanes		0.30	0.30	0.30
Distance between outer midpoints translation-axis		5 * 5	4,9*4,9	4,7*4,7
Distance between inner midpoints translation-axis		5,6 * 5,6	5,5*5,5	5.3*5.3
R curve entry and exit		10.00	10.00	10.00
R curve lane divider entry		12.00	12.00	12.00
R curve lane divider exit		15.00	15.00	15.00
Width overrun area for vehicles with length 22 tot 27 m		5.00	5.00	max 5.00
Speed passenger car [km/h]		37-39	38-39	40

Star roundabout

Characteristics	**Radius and measurements star roundabout**	
R_{inside} of the inner lane	**R1**	**12**
$R_{Outside}$ of the inner lane	**R2**	17.10
R_{Inside} of the middle lane	**R3**	17.40
$R_{outside}$ of the middle lane	**R4**	22.30
R_{Inside} of the outer lane	**R5**	22.60
$R_{outside}$ of the outer lane	**R6**	27.30
Physical barrier between driving lanes		0.30
Distance between outer midpoints translation-axis		5*5*5
Distance between inner midpoints translation-axis		5,6*5,6*5,6
R curve entry and exit		10.00
R curve lane divider entry		12.00
R curve lane divider exit		15.00
Width overrun area for vehicles with length 22 to 27 m		5.00