This is a summary of a presentation at the office FHWA in January 2009

Based on “Pedestrian and Bicycle-Friendly Roundabouts; Dilemma of Comfort and Safety”, a presentation in 2003 at the Annual Meeting of the Institute of Transportation Engineers in Seattle in 2003, ITE, Washington D.C, USA.

Updated 9 February 2012
Essential characteristics of roundabouts

- Unambiguous points of conflict
- Low speeds
- Suitable for large vehicles
- Only Forgivable Obstacles

The key characteristics of a modern RA are:
- Unique conflict points
- Low speeds
- Suitable for large vehicles
- Only forgivable obstacles for entering vehicles
Research has shown that there is a high correlation between collision-speed and the risk of fatal injury.

This exhibit shows that a reduction of speed from 50 kilometres an hour to 32 km/h, decreases the pedestrian’s chances of death by a factor of about 5.
(1) How to realise speed reduction and keep roundabouts accessible for heavy traffic? Here you see a solution for the combination of the requirements for safety and accessibility.

(2) 90-degree angle between approach and circulatory roadway.

(3) Limited width of circulatory roadway.

(4) Central apron offers an additional roadway width for trucks.

(5) Optional apron in the axil (or armpit) between entrance and roundabout (which also offers an additional roadway for trucks). Also you can apply an apron in the axil between roundabout and exit.

This is what I would tell you about the single-lane roundabout.
Finally the effect of obstacles on the RA island
The requirement of Stainable Safety means that the RA sign in case of a collision should bent down totally and not break into pieces, that could break the windshield of a car and cause injuries for the car occupants.

This requirement of safe post crash behavior holds for all objects in the central island.
The second dilemma is about the radius itself.

This dilemma consists of two parts

First the dilemma regarding only safety (2a)
- Low speeds at the RA require a small radius
- Low speeds for straight on going vehicles require a large radius.

The second dilemma is between safety and capacity (2b)
- The Capacity requirement is: splitter islands of branches not too small;
- The Safety requirement is: splitter island not too large, because then vehicle tracks become too smooth.

Wider central islands require a larger RA radius to obtain an optimal speed reduction.

Increasing vehicle path curvature – that means decreasing the radius of the vehicle path curve – can be reached by increasing the roundabout radius up to an optimum, which depends on:
- the angle between the connecting legs;
- the width of the circulatory roadway;
- the width of the splitter islands in the connecting legs.

(Voor het berekenen van de maximale doorrij snelheid luidt de CROW-formule: \( v_{\text{rijcurve}} = 7.4 \times R_{\text{rijcurve}} \times \sqrt{R} \) in [m], \( v \) in [km/h].)
Fastest Path through Single-Lane Roundabout in the Netherlands

When there are no vertical elements, everywhere 1 m distance to the lane-boundaries.
Pass Through Path when Roundabout Leg’s Angle is 120°

When the angle between the legs is between 90 and 180 degrees, then the pass-through speed will increase substantially. To reduce the speed, you have to increase the roundabout radius.

Summarizing:
The requirements of safety are:
- Low roundabout’s traffic speed: roundabout radius should not to be too large.
- Low pass through speed: roundabout radius not too small.

versus
The requirements of capacity:
- Is there enough time for detecting cars leaving the roundabout at the same leg as you are entering? That means that the splitter island width has not to be too small.

It is a challenge to find the optimum measure of all the basic elements of the roundabout:
- The angle between the connecting legs.
- The roundabout radius.
- The width of the circulatory roadway.
- The width of the splitter islands in the connecting legs.
The aprons should not be too steep. This is a new concept for an apron around the central island in The Netherlands:

The apron:
- should be separated from the carriageway by a rumble strip rising 7 cm over 10 cm.
- should have less super elevation than the carriageway (to avoid overturn trucks).
This will prevent cars using it and will not give unnecessary discomfort for trucks.

(to prevent private cars to cut off path curvature and to avoid unnecessary discomfort for trucks).
This slide gives the recommended design of the mountable aprons in the center and armpits. This part is very important to solve the dilemma between safety and ride ability of all roundabouts.

In the past we made some mistakes with this detail, resulting in:
- Higher pass through speeds;
- Capsizing trucks
- Higher costs of maintenance.
How to Design Safe Double-Lane Roundabouts?

Problem: sideways collisions (1)

Three causes:

a) exiting the roundabout from the inner lane;
b) weaving movements;
c) entering roundabout with too high speed.

Safety Dilemma of Double-Lane Roundabouts

The problem is: How does one design safe double-lane roundabouts?

As said, than we meet with the problem of sideways collisions.

Three causes have to be mentioned:

a) Exiting the roundabout from the inner lane (therefore the Dutch roundabout guide earlier recommended double-lane roundabouts with single-lane exits).
b) Weaving movements on the circulatory roadway.
c) Entering the roundabout with a too high speed, which results in path overlap.

The third cause leads to different solutions to solve that problem.
Problem: sideways collisions (2)

Solving the consequences of too high entering speeds, we meet with the dilemma between:
• Reducing the risk of sideswipe collision

and

• Reducing the severity of collisions with pedestrians and cyclists

Safety Dilemma of Double-Lane Roundabouts

The third cause leads to different solutions to solve that problem. But to reduce the problem of sideways collisions caused by too high entering speeds, we meet with a dilemma at a concentric two-lane roundabout. The dilemma between:
- reducing the risk of sideswipe collisions
and
- reducing the severity of collisions, especially with vulnerable road-users
Path Overlap at a Double-Lane Roundabout

Increasing vehicle path curvature creates greater side friction

Dilemma:
• Accepting higher risk of sideswipe collisions

or
• Accepting higher severity of collisions with pedestrians and cyclists by higher speed

Result: increasing risk of sideswipe collisions

At multi-lane roundabouts increasing vehicle path curvature creates greater side friction between adjacent traffic streams, which can result in more vehicles cutting across lanes, increasing risk of sideways collisions.

So we need to deal with a dilemma between:

Accepting higher risk of sideswipe collisions or
Accepting higher severity of collisions with vulnerable road users by higher speed of fast traffic.

(How to solve this dilemma?)
How to solve this dilemma?

The challenge is to develop a roundabout with high capacity, which is still safe - both for motorists (fast traffic) and vulnerable road users (slow traffic).

The preconditions for that solution are:
- no weaving at the roundabout;
- yield to no more than two lanes;
- low speeds.

The result is called Turbo roundabout.

Since 2000 about 70 roundabouts of this principle have been built in the Netherlands.

What are the features?
- Spiral lane marking.

Mountable lane dividers, which underline the spiral marking: the traffic is induced to keep its own lane. This helps to prevent sideswipe collision (because it is difficult to cut off lanes).

Additionally: mountable splitter islands which introduce the mountable lane dividers at the roundabout.
(1) This graph shows the relationship between the pass through speed (vertically) and the inner radius (horizontally) of several types of roundabouts.

Red: the single lane roundabout

Yellow: the double lane roundabout without lane-dividers

Green: the turbo roundabout with lane-dividers

The impact of lane-dividers is obvious.

(2) Without lane dividers the minimum pass through speed on double-lane roundabouts is reached by a radius of 30 meters at a level of 48 km/h (30 mph)

(3) At turbo roundabouts, you need a smaller radius and the speed reduction looks like the reduction on a rural single lane roundabout - at a level of 38 km an hour.
When the width of the splitter island is 7 meters, the minimum speed will be reached with a larger radius.

The accepted centrifugal acceleration is ca. 0.5g. (ca.5 m/s²).
Perhaps, you will question the quality of traffic flow at this type of roundabouts.

Here you see a comparison of roundabouts and traffic lights, which Martijn de Leeuw has calculated by a simulation model HUTSIM at Delft University of Technology.

Horizontally you see the total traffic volume, that enters the roundabout.

Vertically the average delay at the main road, inclusive geometric delay (because of speed reduction or a larger route).

As the volume does not reach the capacity limit, the delay at a roundabout is obviously less than at a signalized intersection (as you can see at the graph).
Effects of Roundabout Construction on Safety

Province of South-Holland monitors yearly the safety effects of roundabout construction
Note: these are roundabouts outside built-up areas

Results of comparison of pre and post research on single lane roundabouts where bicycle traffic has no priority

<table>
<thead>
<tr>
<th>Pre and post period</th>
<th>Injury Accidents</th>
<th>Total Accidents</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>All Ra</td>
<td>After 1994</td>
</tr>
<tr>
<td>Pre period crossing with priority</td>
<td>1,24</td>
<td>0,98</td>
</tr>
<tr>
<td>Post period with roundabout</td>
<td>0,23</td>
<td>0,26</td>
</tr>
<tr>
<td>Decrease</td>
<td>- 81 %</td>
<td>- 73 %</td>
</tr>
<tr>
<td>Country wide reduction percentage: 70 %</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Effect on safety of the building of RA at priority intersections

The table shows the results of the yearly monitoring of the safety effects of the building of RA’s at the road network of the province of Zuid-Holland until 2003.

It should be remarked that the safety effect will gradually become less because the more dangerous intersections were rebuilt first.

This is illustrated by the reduction percentage of RA’s built after 1994, having a reduction of only 73 % (in stead of 81%).

We therefore recommend to use a percentage of 70 as a general applicable number.
Replacement of signalized intersections by roundabouts

There are too little research data available to give a reasonable accurate effect. For the time being, we use a reduction of accidents with victims: 70% This is a reduction factor of 0.3

Effect on safety of the building of RA at signalized intersections

There are too little research data available to give a reasonable accurate effect of the replacement of signalized intersections by RA. For the time being South-Holland works with an estimate. Reduction of accidents with victims: 67% This is a reduction factor of 0.33 The calculation method shown is an approximation.

Note: reduction percentages should not be added but multiplied.

Reduction Factor = 1 - (Reduction %) / 100
Effect of Roundabouts on Safety Vulnerable Road Users

Owen Arndt and Rod Troutbeck at International Symposium on Highway Geometric Design Practices in 1995 stated:

“Numerous studies show: “Roundabouts are a safer intersection type for vehicle occupants and pedestrians, but may be more dangerous for cyclists.”

Nevertheless by comparing 27 intersections before and after the building of roundabouts by province South-Holland we found the reduction of casualties among cyclists and moped riders to be in the same range as the reduction of casualties among motorists, (both reduced by about eighty percent).

Results of before and after situation of 41 single-lane roundabouts where cyclists and moped-riders have to yield right-of-way.

Accidents in a 3 year period in the province of South-Holland

<table>
<thead>
<tr>
<th>All types of accidents</th>
<th>Injury accidents</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before 5,2</td>
<td>1,36</td>
</tr>
<tr>
<td>After 2,51</td>
<td>0,25</td>
</tr>
<tr>
<td>Reduction 52 %</td>
<td>81 %</td>
</tr>
</tbody>
</table>
Three different solutions are possible for bicycle traffic:

1. On the circulatory roadway, cyclists mixed with motorized traffic.
2. Marked bicycle lanes on the circulatory roadway, next near the roadway for car traffic.
4. For the separated bicycle path are two possibilities of the right-of-way:
   a. (mopeds) and cyclists do not have right-of-way.
   b. or cyclists have priority.

As the following graph will show, marked bicycle-lanes near the roadway are very dangerous.
This diagram shows the number of casualties per bicycle facility as a function of the volume of motorized traffic.

As I have told, this graph shows that a roundabout with a cycle lane gives the highest risk for cyclists and moped riders for injuries. The position of bicycles just behind the motor traffic is dangerous at a roundabout. Motorists in a curve can not see/detect clearly cyclists riding next to them.

It is obvious that a cycle track gives the lowest risk for injuries. In the survey only bicycle paths without right-of-way were represented.

Finally, up to a 6000 cars a day, the difference between alternative solutions is not significant. Under condition of low speed at a small roundabout a solution with cyclists between motorized traffic (without bicycle facility) looks rather safe too. In the Dutch Roundabout Guideline above 6000 veh/day only bicycle tracks are recommended.
Recommendations concerning Right-of-Way and the design of roundabouts

The Dutch Institute for Guidelines (CROW) recommends:

A. Do not mark bicycle lanes at roundabouts, but build separate bicycle paths (tracks).

B. The right-of-way concerning cyclists:
   1. Outside built-up areas:
      do not give cyclists and pedestrians right-of-way
   2. Within built-up areas:
      give pedestrians and cyclists right-of-way

(1) The first recommendation of the Dutch Institute for Guidelines concerning bicycles at roundabouts is:

(2) because of safety reasons: Don’t mark bicycle-lanes at roundabouts, but build separate bicycle paths.

(3) The Dutch guideline gives two recommendations concerning right-of-way:

• Outside built-up areas there is agreement that we do not give right-of-way to cyclists and moped riders on cycle paths.

• Within built-up areas the recommendation is: give right-of-way to pedestrians and cyclists.
This is the geometric design for a roundabout that does not give pedestrians, cyclists and moped riders right-of-way.

Already I dealt with this solution, which is very safe: the reduction of casualties of cyclists and moped riders after construction is the same as the reduction of casualties among motorists (by a factor 5).

The recommendation for outside built-up areas is solid (clear-cut).

Only one condition is required. Cyclists and moped riders have to do a veering movement before crossing the roundabout leg. This is in order to reach a higher level of awareness that they are going to undertake a crossing of a type in which they have to give the right-of-way. Also fast cyclists and moped riders have to reduce their speed, so that the time for anticipation will increase.

Solid = safety of the solution is not strongly influenced by a little change in the design.

Clear-cut: for road users is the situation easy to understand what action to take.
Geometric Design for a Roundabout that Gives Cyclists Right-of-Way Within Built-Up Areas

- Without moped users on the bicycle track.
- Enough distance between roadway and track is essential for cyclists’ safety.

(1) This solution is recommended within built-up areas, without moped users on the bicycle track. The pedestrians do have right-of-way on the pedestrian crossing, implemented as a zebra crossing. The cyclists have right-of-way by give-way-road-marking. It is convenient for pedestrians and cyclists. Probably, for pedestrians this design doesn’t give safety problems. For cyclists it does. In this design, trucks are very dangerous for cyclists.

(2) The absence of mopeds at the track is essential to improve the safety. In built-up areas they have to be mixed with the traffic at the circulatory roadway.

(3) In particular the distance between the circulatory roadway and the cycle track is very important for the cyclist’s safety at this type of roundabout.
This table condenses the research into safety of roundabouts related to the design of the roundabout.

The upper row gives the results of roundabouts where fast traffic has to yield right-of-way to slow traffic, where the distance between the roundabout roadway and the cycle track is 5 meters.

The lowest row gives the results of roundabouts where slow traffic has to yield right-of-way.

The difference in safety is a factor 2, which is significant. For accidents occurring between fast and slow traffic, the difference could be multiplied by a factor of 4.

But because of the low absolute number of accidents, the priority of cyclists in build-up area’s is commonly accepted.

(Gerts, F.H.J. (2002). CROW-tonde of rotonde? Een onderzoek naar de verkeersveiligheid op enkelstrooksrondes binnen de bebouwde kom. Stagerapport. NHTV, Breda, coached by SWOV Institute for Road Safety Research and

Safety Conclusions Right-of-Way Cyclists

Roundabouts with priority for bicycle traffic compared to No-Priority for bicycle traffic:
• Twice as many accidents with injuries
• Four times as many accidents with injuries with cyclists;
• Seven times more accidents with “hospital injuries”.

When replacing crossings with priority by roundabouts with priority for bicycle traffic:
• Reduction total number accidents with injuries
• Possible increase of accidents with injuries.
Cyclists’ Safety related to the Right-Of-Way

The SWOV Institute for Road Safety Research in the Netherlands did some research after the safety of different kinds of priority for cyclists at roundabouts.

➢ Summarizing

It is possible to state, that on Roundabouts where cyclists have right of way compared to roundabouts where slow traffic has to yield right-of-way, the differences are:

• Two times as many injury accidents;
• Four times as many injury accidents with cyclists.
• Seven times as many hospital accidents.

But because of the low absolute number of accidents, the priority of cyclists in build-up area’s is commonly accepted.
But sometimes the safety problems need to take action.

Here you see a recent picture taken in my residential town: the administration closed a cyclist’s crossing together with a crossing for pedestrians, because otherwise cyclists would use the footpath.
But cyclists are inventive.
A car at one lane can cut off the sight of motorists and cyclists to each other.

When a bike has the right of way, it is a problem: the motorist does not see a road-user which has the right of way.

When the motorists have the right of way, the cyclist, does see the other car which has the right of way, and will not cross.

So it is strongly advised against applying right-of-way for cyclists crossing a two-lane branch of a roundabout.
This slide shows the design of bicycle crossings at double-lane roundabouts.

Firstly there has to be awareness of the conflict partner.

Secondly, when the process of observing-deciding–acting has to be repeated within 2 seconds, the chance of faults is increasing. Crossing two double lanes requires a lot from the slow road users. An anticipation time of 2 seconds between two decisions would be desirable. For cyclists, this can be achieved by applying a chicane (also called: Jog or S-curve) through a splitter island having a width of 7 meters.

Because of the slower speed of pedestrians, a distance of 3 meters between the approaching leg and the exit leg will be sufficient to provide more than 2 seconds time to anticipate.
This picture shows a bicycle chicane (or jog or S-curve) in the median, located immediately next to a pedestrian crossing at a double-lane roundabout.
Cyclist at the Chicane in Median

The cyclist at the jog is facing the traffic. (That occurs in both directions.)
As you see, to finish this, using the jog does not demand a high level of mental load. There is enough mental space to notice the traffic on the roundabout departure leg, or to observe the photographer, as in this case.