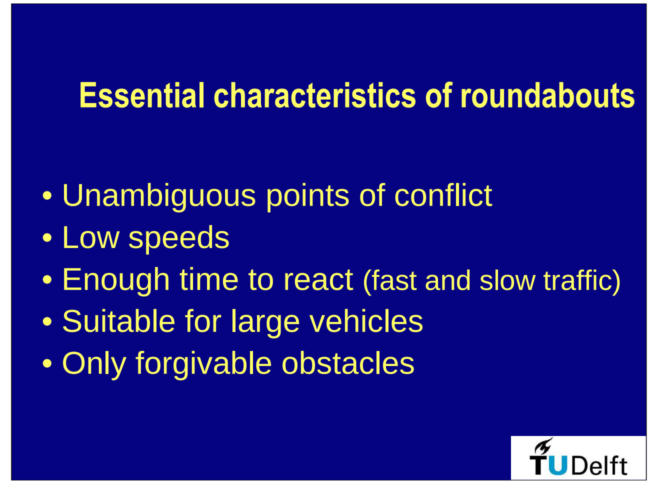
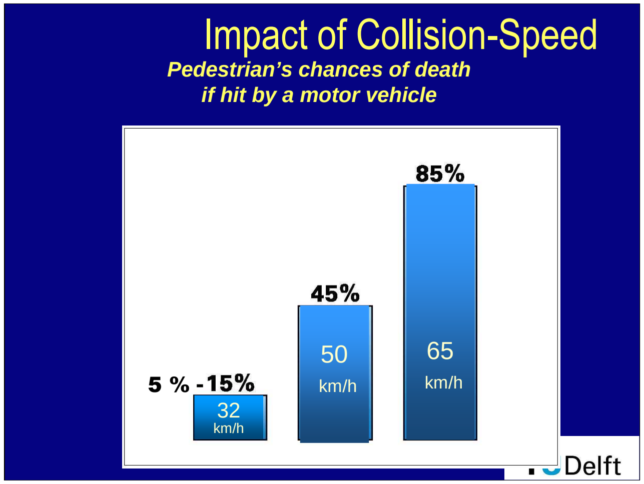
Roundabouts in the Netherlands; Development and experiences

International Roundabout Design and Capacity Seminar, 1st July 2011, Stockholm
In connection with the TRB 6th International Symposium on Highway Capacity and Quality of Service.

(Extended Version)



These are the key characteristics of a modern roundabout

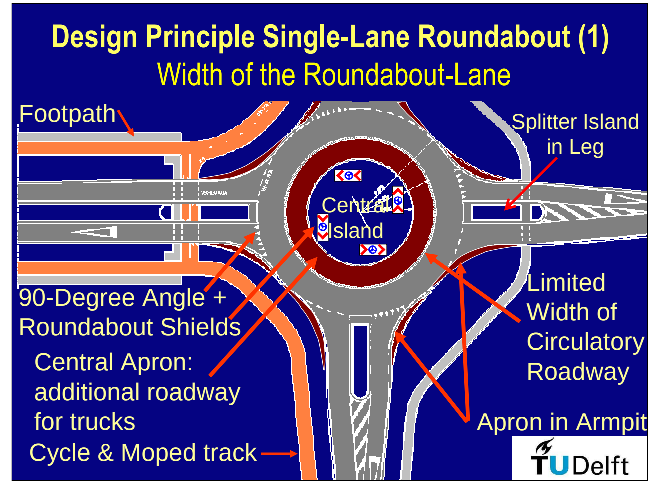


Impact of Collision-speed

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.

So speed reduction at conflict points is essential for safety.



Designing traffic infrastructure deals always with solving dilemma's.
The first dilemma deals with the circular roadway. The question is: 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

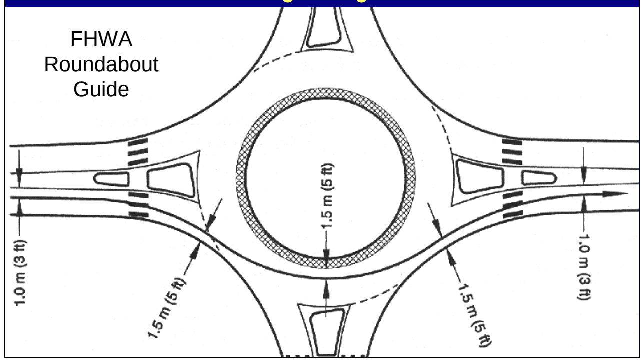
(1) 90-degree angle between approach and circulatory roadway *(safety).*

(2) Limited width of circulatory roadway *(safety).*

(3) Central apron offers an additional roadway width for trucks (*combination safety and pass ability*).

(4) Apron in the armpit between entrance and roundabout and roundabout and exit, which also offer an additional roadway for trucks (*combination safety and pass ability*).

Design Principle Single-Lane Roundabout (2)
Dilemma Radius of Roundabout
Fastest Path through Single-Lane Roundabout



The second dilemma is about the roundabout radius itself. This dilemma consists of two parts.
First the dilemma regarding *only safety (2a)*
- Low speeds at the Roundabout require a small radius.
- Low speeds for straight on going vehicles require a large radius.

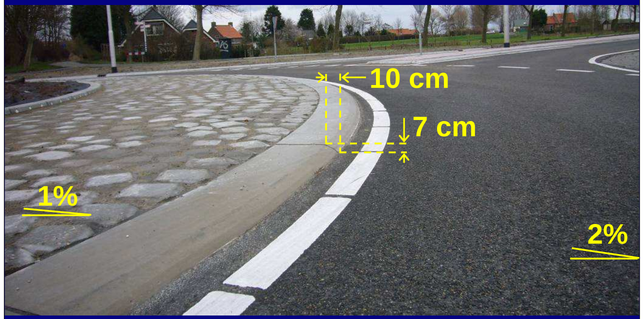
-*The second* dilemma is *between safety and capacity* (2b)
- The Capacity requirement is: splitter islands of branches not too small;
- The Safety requirement is: splitter island not too large, because then vehicle tracks become too smooth.

Wider central islands require a larger Roundabout 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.

These are very basic principles in designing roundabouts, but mostly not mentioned in guidelines.
My statement is: these principles always have to be mentioned in guidelines!

New Rumble Strip in Practice



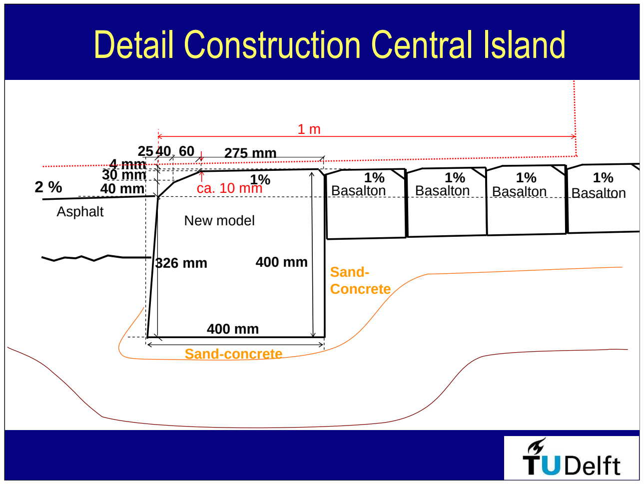
The aprons should not be too steep. This is a new concept for an apron around the central island in The Netherlands:

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).

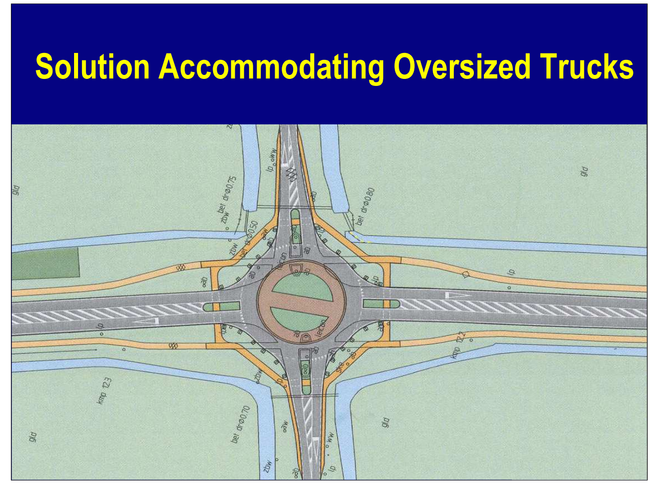


Here the central apron in detail.

The dimensions of the rumble strip (40 x 40 cm) here are based on a length of 2 m. These at are constructive requirements

The traffic requirements of a rumble strip are only:

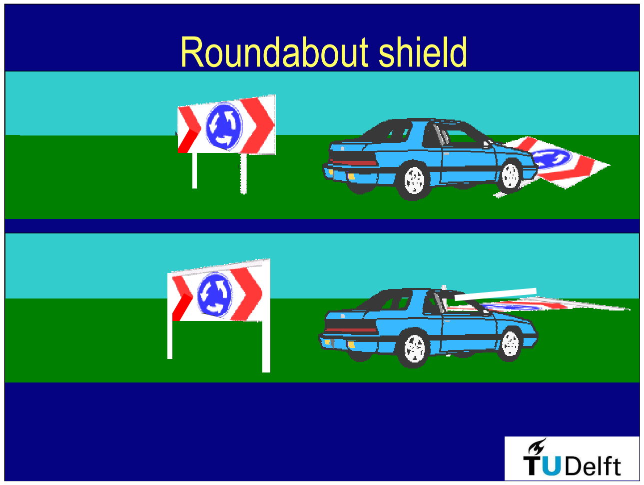
rising 7 cm over 10 cm.



This solution is used in the Netherlands for accommodating oversized trucks.

The dimensions of the aprons are accommodating standard oversized trucks, but for trucks needing an escort this rotated pass-through in the central island offers an extra possibility, which does not reduce the functionality of the roundabout.

Here approaching the rotated pass-through in the central island from a high point of view.



The effect of obstacles on the Roundabout island

The Roundabout Shield is very important outside build-up areas.

I saw an article in *Straßenverkehrstechnik von Spahn and Bäumler* comparing the impact on safety of tangential or curved connecting branches and branches with right angles. But the article was illustrated with a photo without roundabout shields at a roundabout with right angled connecting branches. That means, the authors don't understand, that the safety principle of a right angle requires cutting off the horizon.

Further on, the requirement of Sustainable Safety means, that the roundabout-shield in case of a collision should bent down totally *(Above)* and not break into pieces *(Below),* that could break the windshield of a car and causes injuries for the car occupants.

That we call the safety forgiveness of solutions. This requirement of safe post crash behavior holds for all objects in the central island.

With all these requirements, the modern single lane roundabout is a safe solution for intersections.

Spahn, V., G. Bäumler (2007). Sicherheit von Kreisverkehrsplätzen und Lichtzeichanlagen in Bayern. *Straßenverkehrstechnik*, 7, pp. 357-362, Germany, 2007

Effects of Roundabout Construction on Safety

Province of South-Holland monitors 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

Pre and post period 3 years	Injury Accidents All Ra	Injury Accidents 1994-2002	Total Accidents All Ra	Total Accidents 1994-2002
Pre period crossing with priority	1,24	0,98	4,63	3,86
Post period with roundabout	0,23	0,26	2,31	2,06
Decrease	- 81 %	- 73 %	- 50 %	- 47%

Injury decrease for new roundabouts: 70 %

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Effect on safety of the building of RA at priority intersections

The table shows the results of the monitoring of the safety effects of the building of roundabouts at the road network of the province of Zuid-Holland up to 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.

Effect of Roundabouts on Safety Vulnerable Road Users

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

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

Comparison roundabouts built by Province South-Holland in rural areas:
(27 roundabouts 4 years before and after construction):

Casualties	Before	After	Reduction
Total :	144	28	**- 81 %**
Cyclist + moped :	47	8	**- 83 %**

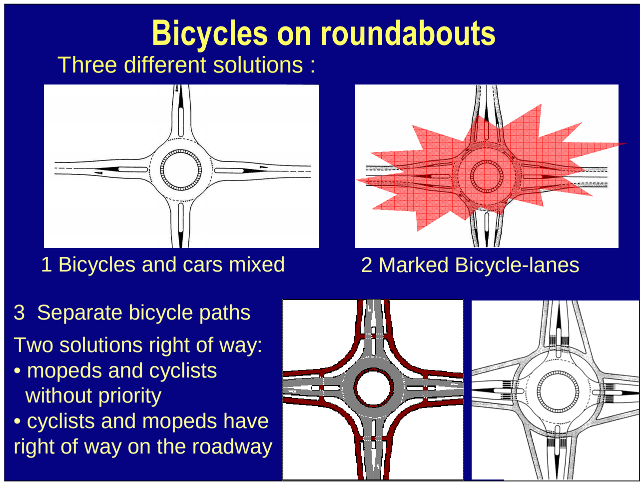
Effect of Roundabouts on Safety of Vulnerable Road Users

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 motorist, (both reduced by about eighty percent).

The conclusion may be: single-lane roundabouts may be the safest type of intersections for all road users, on condition applying the right solution for crossing cyclists. What are these conditions?



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.

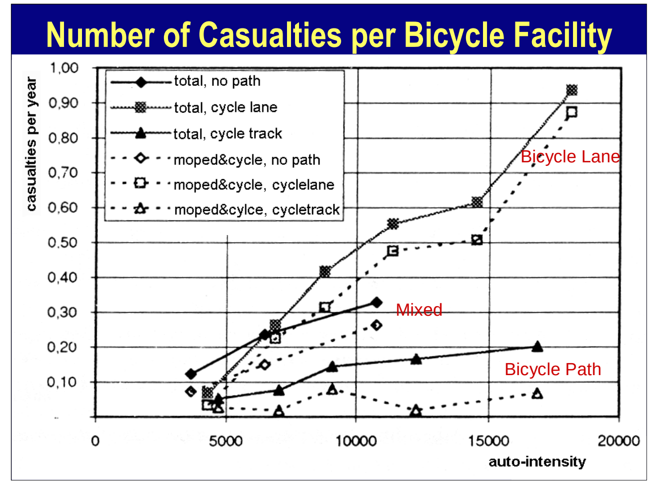
3 Separated bicycle paths.

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.



(1) This diagram shows the number of casualties per bicycle facility as a function of the volume of motorized traffic.

(2) 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.

(3) 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.

(4) 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

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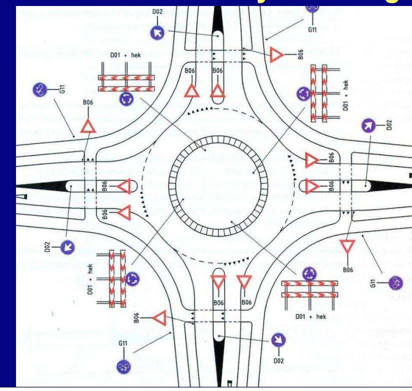
(1) The first recommendation of the Dutch Institute for Guidelines concerning bicycles at roundabouts is:

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

(3) The Dutch guideline gives two recommend<u>a</u>tions concerning right-of-way:

- Outside built-up areas there is agreement that we do <u>not</u> 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.

Geometric Design for a Roundabout that Does Not Give Cyclists Right-of-Way



Outside built-up areas also mopeds at the cycle track

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This is the geometric design for a roundabout that does <u>not</u> 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 4 up to 5).

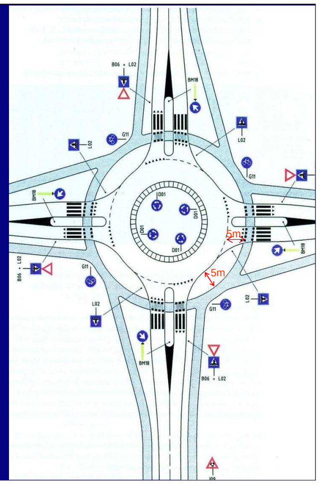
The recommendation for outside built-up areas is solid (clear-cut).

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.
- A minimum distance of 5 m is recommended between roadway and track.



(1) This solution is recommended <u>within</u> 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 safety. In built-up areas they have to be mixed with the traffic at the circulatory roadway
(3) A minimum distance of 5 m is recommended between roadway and track at this type of roundabout. But the results of research about the safety effect of this distant requirement are not clear.

Effect of priority on Safety

Priority of bicycles	Number of roundabouts examined	Average casualties a year	Difference
Priority ≥ 5 m	15+17	0.6	Very Significant
Without priority	30	0.3	

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 enkelstrooksrotondes binnen de bebouwde kom. Stagerapport. NHTV, Breda, coached by SWOV Institute for Road Safety Research and

Weijermars, W.A.M. (2001). *"Voorrang aan veiligheid op rotondes"*, Afstudeerscriptie Universiteit Twente, Enschede, september 2001, also coached by SWOV Institute for Road Safety Research)

SWOV Conclusions Safety Cyclists

Roundabouts where
cyclists have right of way
compared with
roundabouts where slow traffic has to yield right-of-way:

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

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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.

➢<u>Summarizing</u>

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:

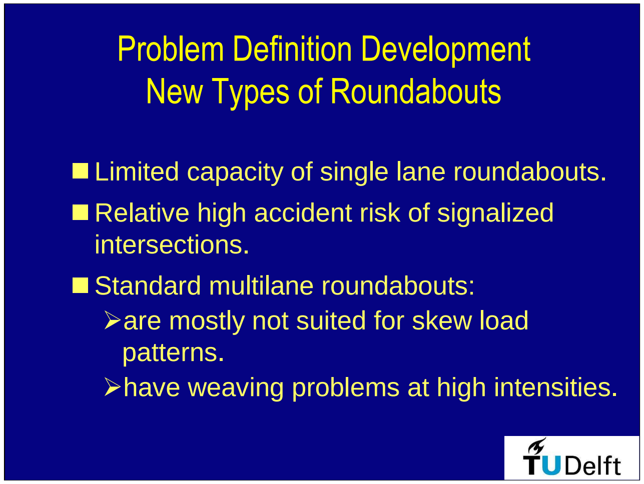
- Two times as many injury accidents;
- Four times as many injury accidents with cyclists.
- Seven times as many hospital accidents.

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

Sweet Lake City (Zoetermeer)

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.



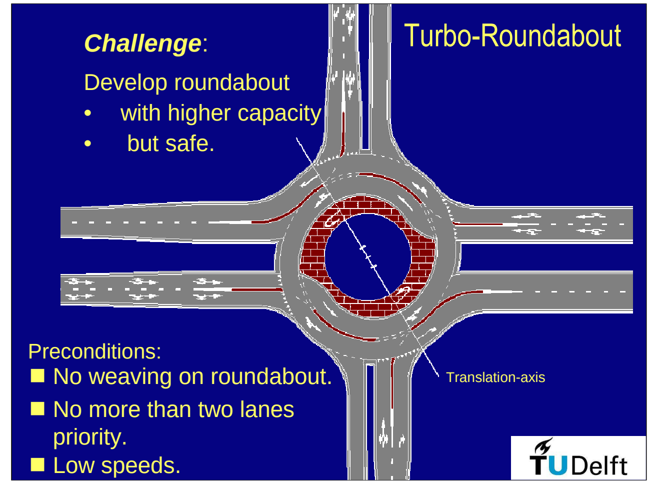
Problem Definition Development New Types of Roundabouts

In 1997 the province ZH had built 85 single-lane RA's. But at many spots that required a roundabout we found that capacity of a single lane type would not be sufficient.

The following dilemma presented itself.

A double-lane Roundabout causes a lot of side swipe collisions. In the past for that reason we replaced old rotaries by a signalized intersection. But afterwards we saw again an increase of injury accidents, especially with vulnerable road users, it est (i.e.) pedestrians, bicyclists and mopeds.

How to solve this problem?



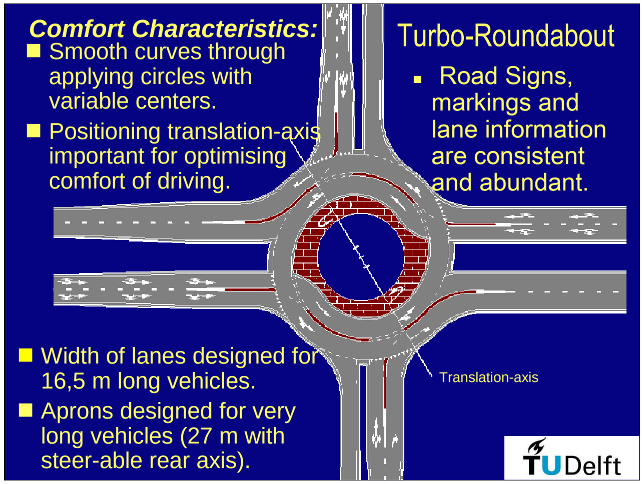
The Challenge was to develop a roundabout

- with a higher capacity than a single-lane roundabout and a roundabout with passing-by facilities
- but with the same safety characteristics.

➢ 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.



How can we fulfill the requirements in the design?

Characteristics relating to comfort for the users

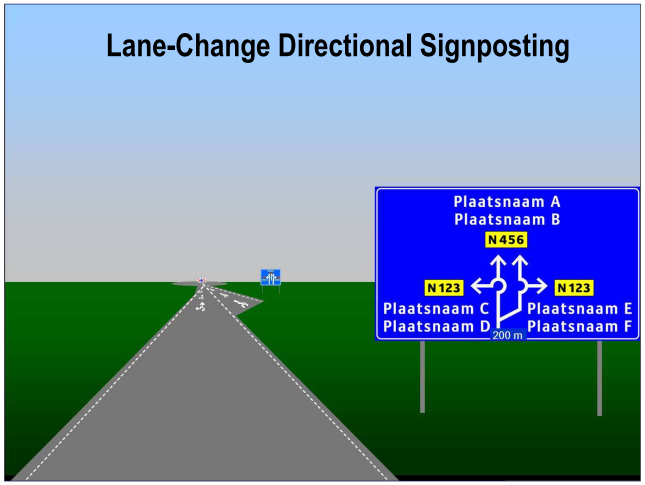
- By applying circles with variable central points the vehicle tracks become smooth. The driving comfort is optimized by positioning the translation axis (that is the axis on which the different central point are positioned) in such a way that for all straight on going vehicles the deflection (and hence the speed) is about the same.

- Lanes have to be chosen so wide, that trucks of 16.5 m length can use the Roundabout without having to use heightened aprons (correct curve widening for the circulatory roadway)

- By applying mountably raised aprons long trucks of 27 m with steer-able back axles can also pass the RA.

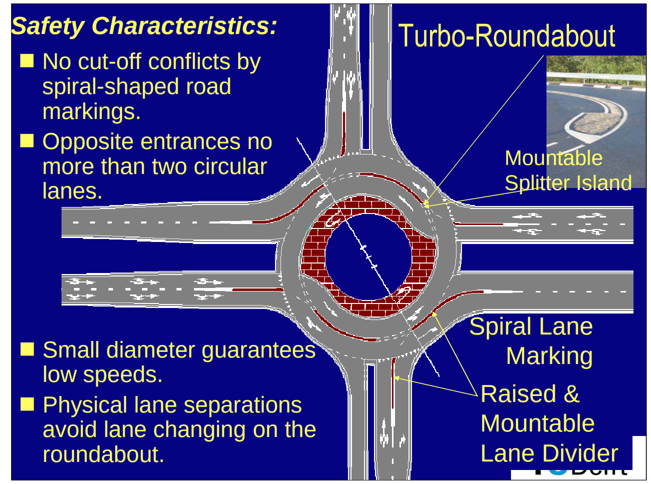
➢ Last but not least: Route signing, road markings and lane information must be consistent and abundant. Because before entering the roundabout, the driver has to choose the right lane. Therefore, redundancy in sign marking and road marking is necessary.

This slide shows a good combination of signposting and road marking.



When the lanes are too short, you need Lane-Change Signposting.

This is now accepted in the Netherlands and and will be implemented in the guidelines.



Implementing safety characteristics in the design

The safety characteristics are:

- No cut-off conflicts by using spiral striping
- No more than 2 continuing lanes at the RA

➢ Guaranteeing low speeds at the Roundabout by using a small diameter:

- Prevent cutting off of lanes by physical lane separations at the RA.
- Apply a good relation between the widths of the splitter islands in connected branches and Roundabout radii, in order to reduce the speed of through going vehicles sufficiently.

Safety Effects of Turbo-Roundabouts in Comparison of Single-Lane Roundabouts

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

Pre and post period 3 years	Injury Accidents Single-Lane Ra	Injury Accidents Turbo-Ra	Total Accidents Single-Lane Ra	Total Accidents Turbo-Ra
Pre period with crossing	1,12	2,4	4,22	11,9
Post period with roundabout	0,19	0,44	2,30	6,06
Decrease	- 83 %	- 82 %	- 46 %	- 49 %

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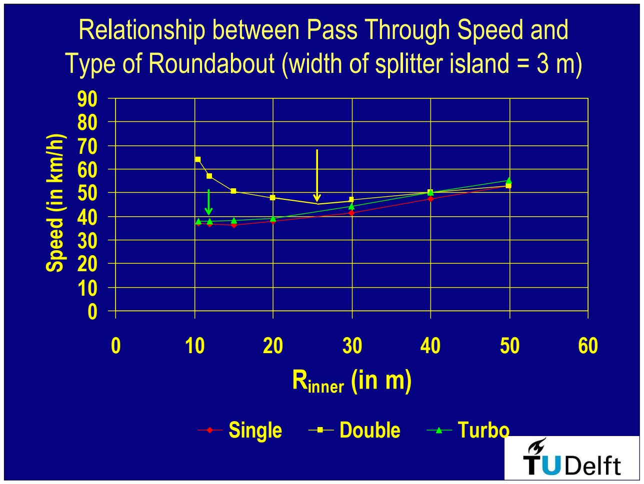
Effect on safety of the building Turbo Roundabouts

This slide shows the safety effects of replacing different kinds of intersection by turbo roundabouts.
It is remarkable, that the decrease of accidents for turbo-roundabouts is comparable with single-lane roundabouts.

There are two reasons for this safety aspect of the turbo roundabout:

a) The speed reduction comparable with single-lane roundabouts.

b) Number of conflict points.



Relationship between Pass Through Speed and Type of Roundabout (width of splitter island = 3 m)

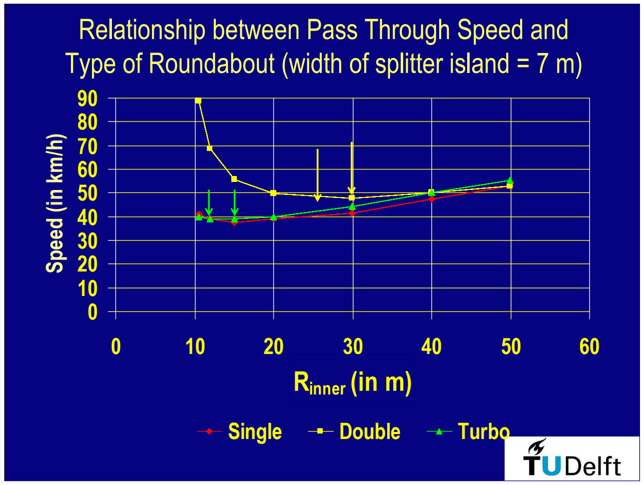
(1) This graph shows the relationship between
- the **pass through speed** *(vertically)* and
- the **inner radius** *(horizontally)* of several types of roundabouts.

Red: the single lane roundabout
Yellow: the concentric compact two-lane roundabout without lane-divider
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)

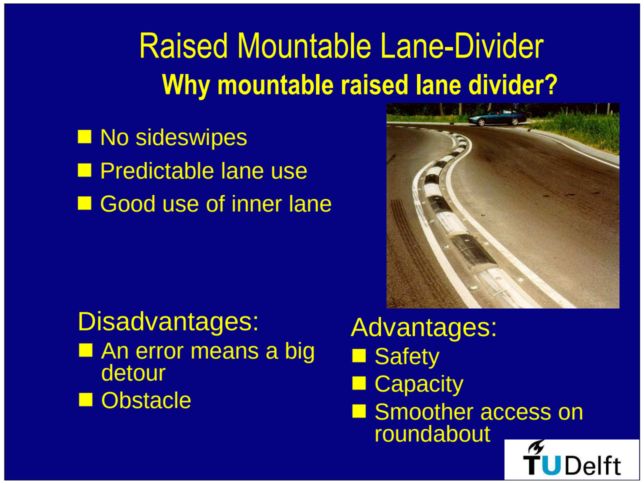
(3) At turbo roundabouts, you need a smaller radius than on a compact two-lane roundabout and the speed reduction looks like the reduction on a rural single lane roundabout - at a level of 38 km an hour.



Relationship between Pass Through Speed and Type of Roundabout (width of splitter island = 7 m)

When the width of the splitter island in the legs are 7 meters, the minimum speed will be reached with a larger radius at a higher level.

This speed reduction is reached by the raised mountable lane divider. This photo shows that the rear wheels of the truck can use the mountable lane divider.



What are the Disadvantages of a Raised Mountable Lane Divider?

- Because it is difficult to mount them, a wrong lane choice implies a detour.
- It is an obstacle which constitutes a danger

Advantages:

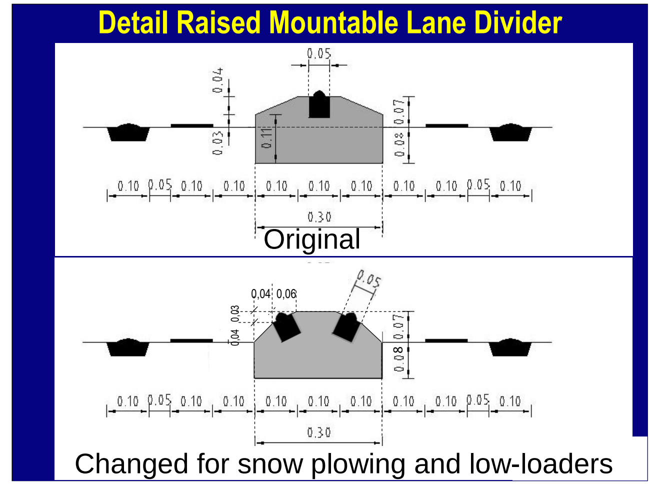
- Speeds become lower causing a large safety benefit
- Capacity increases because the inner lane is well used
- Use of lanes becomes more predictable and makes the entering of the Roundabout easier

Possible problems:

- Strength of the elements; therefore we made them thicker and placed them on the bituminous under layer.
- Skidding risk for motorcycles (but in whole safety effect will be higher for motorcyclists)

Point of attention (also considering liability aspects)

- Contrast and line marking
- Lighting and road reflectors
- Upstream driver information.



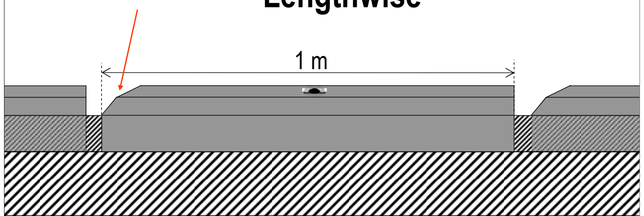
The upper type of lane divider is examined to give a lot of discomfort by crossing (by accelerations in vertical direction), but will not cause too much horizontally forces.

➢A question may be, how to manage snow plowing with raised lane dividers?

In principle it does not differ with problems of snowplowing and the presence of curbs. So I asked people from the Northern part of the States how they handle that problem. And they answered me, that they do not use vertical curbs, but curbs with a slope. So my suggestion is, if problems are expected with snow plowing, to change the raised lane divider in that way.

Because low-loaders will cut-off the reflectors, it is advisable to put them on the slope below the top.

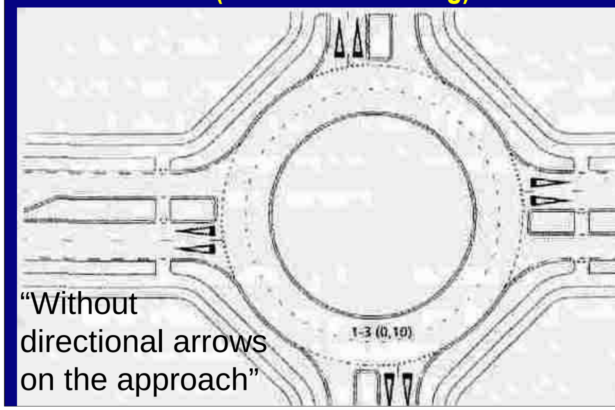
Mountable Lane Divider Lengthwise



Changed for snow plowing
and low-loaders

Lengthwise it is important that in the direction of the traffic flow (I suppose the snow plow will use the same direction) the start of the Lane divider is not vertically.

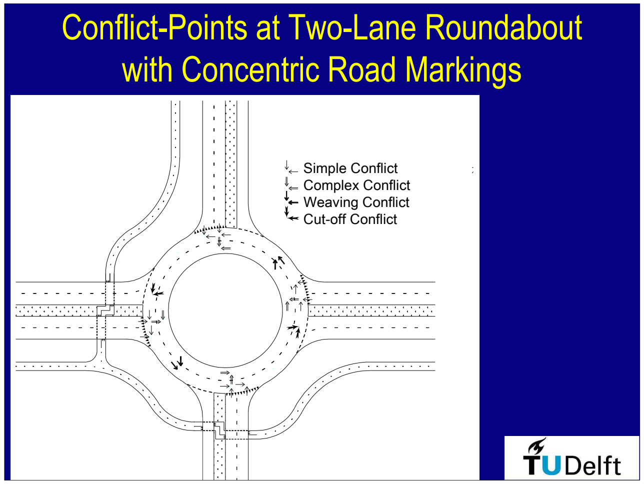
Compact Two-Lane Roundabout (concentric marking)



This has been the standard compact two-lane roundabout in the Netherlands. Essential are the single-lane exits, the same as in Germany.

In the recent Dutch guidelines it is “advised against longer building two-lane roundabouts with concentric marking”. (CROW-publication 257, Turbo Roundabouts, page 11). Now the Turbo Roundabout is recommended.

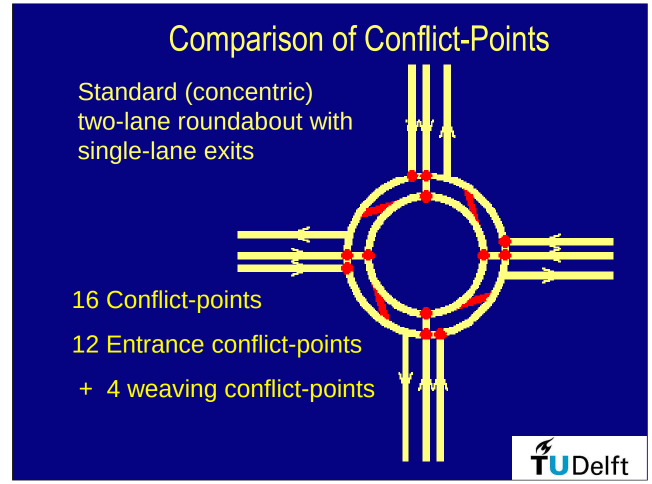
But on existing compact two-lane concentric roundabouts, no pavement arrows have to be applied (because of the Dutch traffic rules, then you never have be able to leave legally the roundabout, after using the left entry-lane).



Earlier only a compact two-lane roundabout with single-lane exits has been recommended. But to compare a concentric double-lane roundabout, with a turbo roundabout you need a Two-Lane Roundabout with two double-lane exits.

Here you see the Conflict-Points on such a roundabout. Different types of conflicts have been distinguished in this picture.

Next pictures show these conflicts more schematically.



Conflict-points Two-Lane Roundabout with One-Lane Exits

These are the conflicts on a standard concentric two-lane roundabout with one-lane exits.

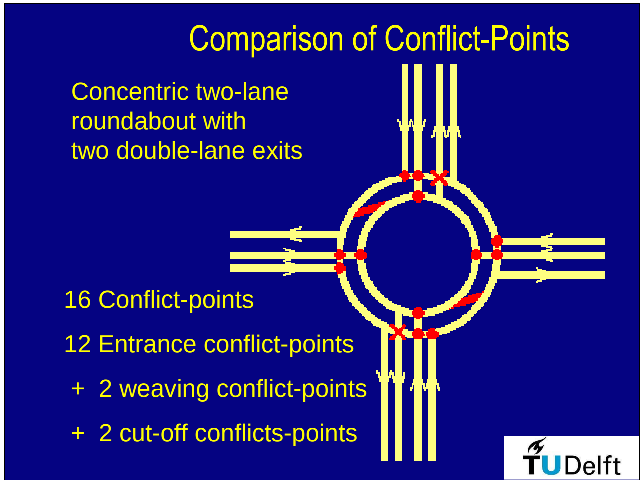
12 Entrance conflicts

+ 4 weaving conflicts

Legend

Point: entrance conflict

Line weaving conflict



Conflict-points on a concentric Two-Lane Roundabout with 2 double-lane Exits

This picture shows the conflicts on a concentric two-lane roundabout with 2 double-lane exits, comparable with the standard turbo roundabout.

12 entrance conflicts

+ 2 weaving conflicts

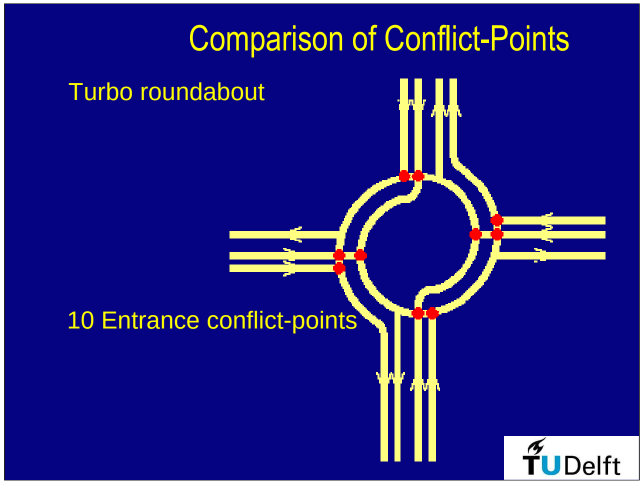
+ 2 cut-off conflicts

Legend

Point: *conflict point*

Line: *weaving conflict*

Cross: *cutting-off conflict*



Conflicts on a Turbo Roundabout

A Turbo Roundabout has 10 conflict points,

(without weaving conflicts and cut-off conflicts)

Legend

Point: *conflict point*

Bikes at Turbo Roundabouts

- Tunnels for vulnerable traffic are preferred
- Conflicts with fast traffic require low speeds
- Hiding problem with right-of-way for cyclists
- Enough time (> 2 seconds) for the process:
  - Observe
  - Decide
  - Act

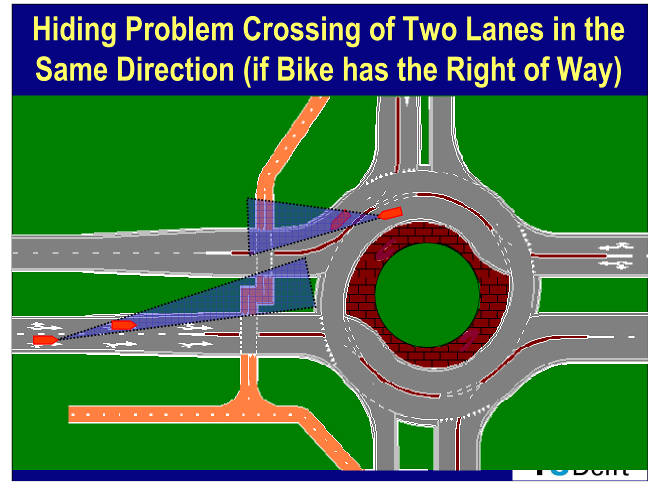
Turbo Roundabouts require especially attention for the safety of vulnerable road-users. The crossing of double lanes poses a higher risk for bikes than crossing a single lane, although the car speeds are low in the vicinity of a turbo roundabout. A new connection of a minor road to a main road with a turbo roundabout requires a grade separated solution: tunnels for bikes and mopeds are preferred in that case.

At existing intersections often space is lacking for such a solution, and a choice has to be made between:
- Application of signalization of the existing crossing or
- Have bikes made an double uncontrolled crossing in the neighborhood of a Turbo Roundabout, where the speed of motorists is reduced.

For the vulnerable road-users is a low speed essential

A special problem are cars which for other car drivers hide cyclists and mopeds.

Further on, it is very important, that the road-users which have to give the right of way – here the cyclists and mopeds – have enough time for the process to observe, decide and act. Between two decisions, an anticipation time of two 2 seconds is required..

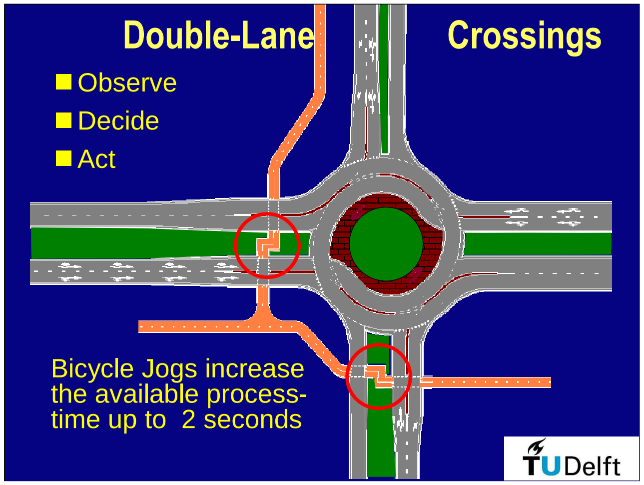


A car at one lane can cut off the sight of motorists and cyclists to each other.

When a bike has the right of way, it is 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 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 .

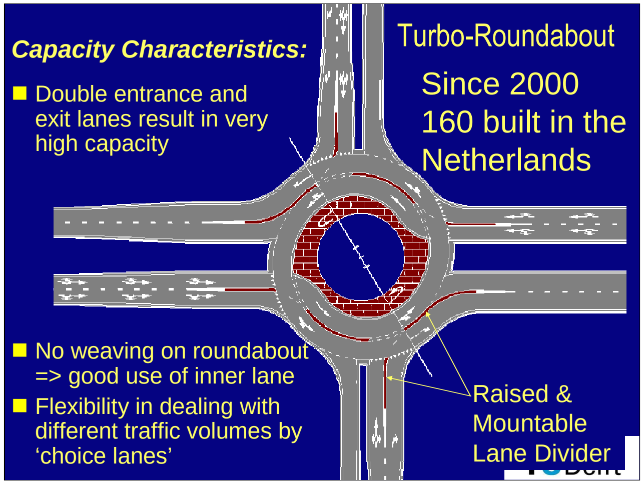
Cyclist at the Chicane in Median

The cyclist at the jog is facing the traffic.
(That occurs in both directions.)

Cyclist Ending Chicane in Median Before Crossing Departure Leg

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.



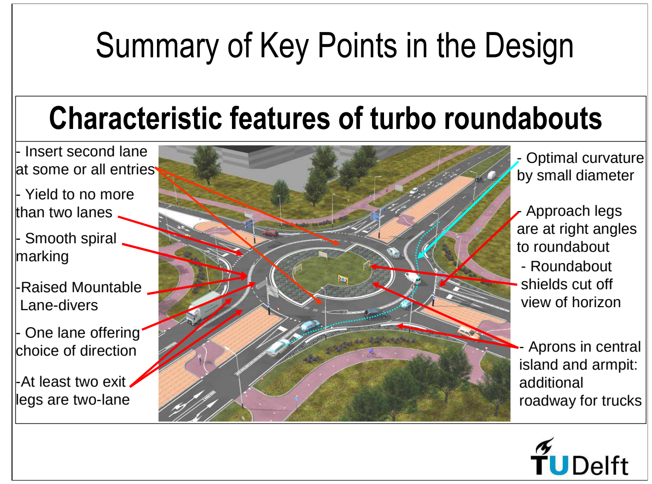
Implementing Capacity Characteristics in the design

• By using 2-lane entrances and 2-lane exits at the main road a high capacity is obtained

➢No weaving on the Roundabout and consequently a well used inner lane

• By offering lane choice to the drivers, different demand patterns can be handled.

Since 2000 about 160 roundabouts of this type have been built in the Netherlands, 107 outside built-up areas and 44 within built-up areas.
(Situation 10 June 2011)

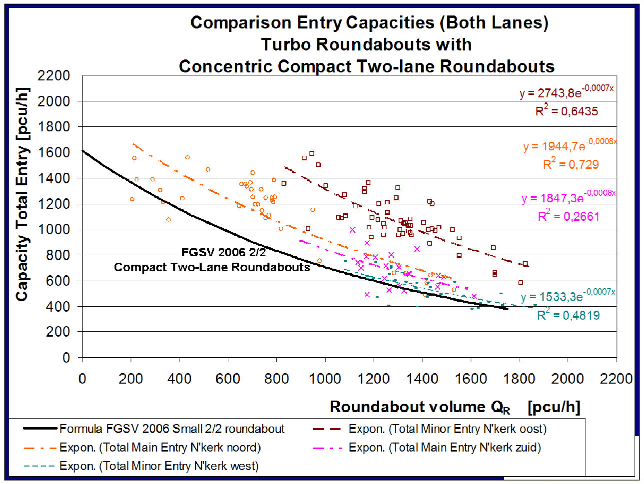


Here all characteristic features are summarized:

- ➢ Opposite at least one entry inserts a second lane (capacity characteristic).
- ➢ Entering drivers have to give priority to no more than 2 lanes (safety characteristic).
- ➢ Smooth lane curves by well applied spiral alignment (comfort characteristic).
- ➢ Raised and mountable lane dividers discourage impatient drivers from cutting in, which avoids weaving at the Roundabout and cut-off conflicts (safety characteristic).
- ➢ Each segment of the roundabout includes one lane on which traffic can choose whether to exit or to continue round the roundabout (robustness characteristic).
- ➢ And corresponding with that, at least two exit legs are two-lane (capacity characteristic).
- ➢ The diameter of the roundabout is kept small, which creates an optimal curvature by small diameter (safety characteristic).

The following characteristics of the Dutch single-lane roundabout are retained:

- ➢ approach legs are at right angles to the roundabout in combination with
- ➢ roundabout shields cutting off view of horizon (safety characteristic);
- ➢ mountable aprons offer sufficient width for long vehicles to use the roundabout (rideablilty characteristic).

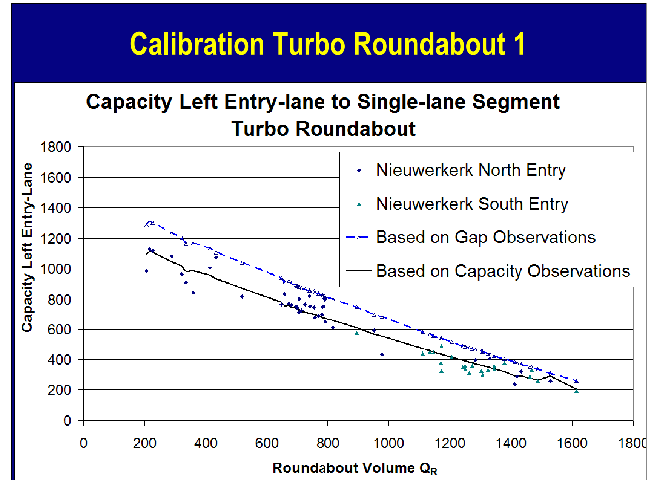


For my PhD-theses I compared the entry volumes of several approaches of a turbo roundabout with the German compact two-lane roundabouts, a study of Werner Brilon and Hanno Bäumer (2004).

As you see, almost on all approaches, the saturated volumes were higher than the results on the concentric compact two-lane roundabouts in Germany.

The reason will be a better use of the left entry-lane and inner lane of the turbo roundabout.

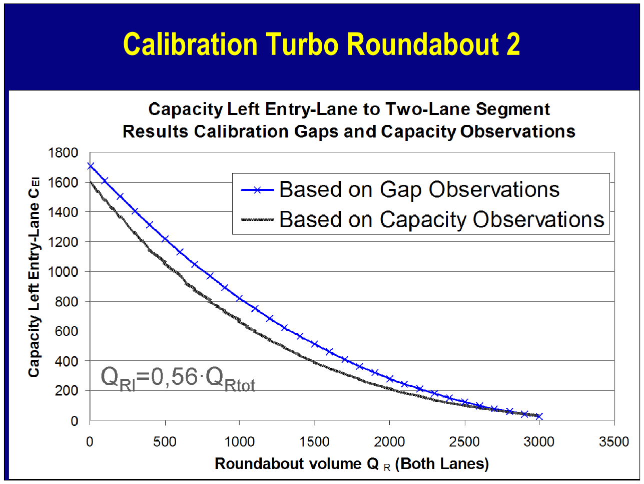
The dissimilarities you see between the different entries of the turbo roundabout are connected with a different use of the right entry-lane: because of the location of the spot, mostly we did not measure saturated flows on the right entry-lane. For instance: the highest and lowest values in this graph are measured on opposite approaches, with the same design.



We did a lot of investigations.

Here you see the results for the capacity of the entry of the left lane of the main road of the turbo roundabout

➢But when I confronted the result with the capacity measurements, I found a lower capacity.



This slide shows the calibration results for the capacity of the left-entry lane of the minor road.

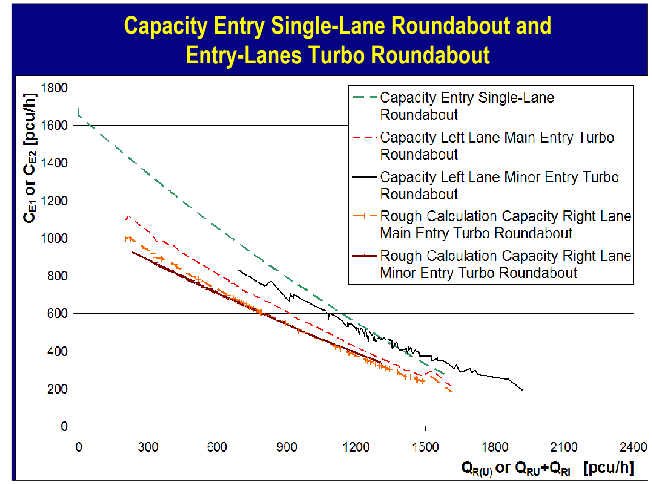
We started with the standard gap-acceptance theory combined with the most sophisticated capacity formula of Hagring for multi-lane Roundabouts.

By the way, because there are here two circulatory lanes, for the graph it is necessary to assume a split of the traffic over the two circulatory lanes. Zero point fifty six was the mean value of the part of the inner lane, we measured, based on volumes in an hour.

➢And also here we found a lower capacity for the left-entry lane of the minor road, based on capacity observations.

It has to be remarked, that we used the same data of the same roundabouts.

So the lesson is: in more complicated situations the assumptions of the gap-acceptance theory lead to an over-estimation of the roundabout capacity.



Here you see the result of the capacity estimations for various types of entries of roundabouts.

For a good understanding: these graphs show the capacity of one entry-lane.

• For the single-lane roundabout it is the capacity of the total entry

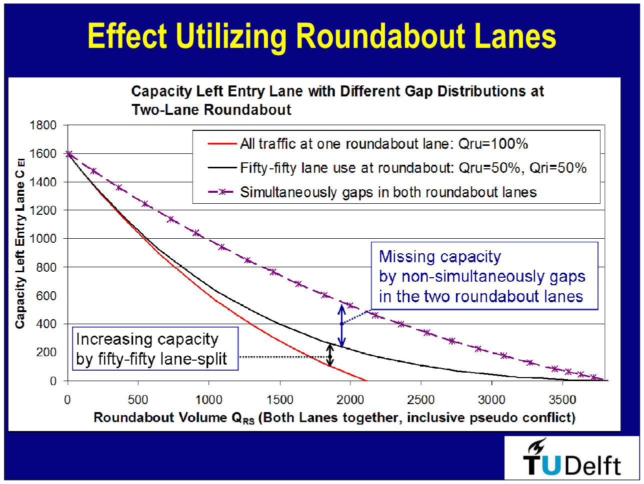
• For the turbo roundabouts it is the capacity of one of the two entry-lanes, both of the main leg as well as of the minor leg.

Remarks:

•For the left entry-lanes it will be an accurate estimation, but for the right lanes it is a rough calculation for the capacity (because we didn't observe enough saturated situations of the right entry-lanes).

•The capacity of one lane is the highest for the single-lane roundabout. The less complicated, the higher the capacity.

•But because of traffic volumes, we need solutions with extra lanes, stipulated that these solutions also have to be safe.



For a high capacity of multi-lane roundabouts, a good use of the both roundabout lanes is important.

We saw it already for the use of the entry-lanes.

But also a good split of the traffic on the roundabout lanes will have a good effect.

The red curve represents the capacity of the left entry-lane, when all circulating traffic is using the outer roundabout-lane.

➢ The black curve shows the increase of the capacity on that entry-lane when on average in an hour, the spit over the roundabout lanes is fifty-fifty.

➢ The pink dotted line indicates the lack of capacity because the gaps in the two roundabout-lanes do not occur simultaneously. Later-on I will give attention to this aspect, related to the effect of metering signals on two-lane roundabouts.

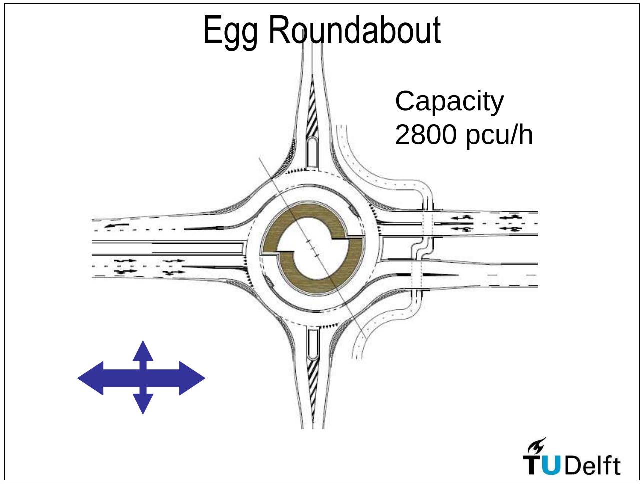
Types of Turbo Roundabouts

- Egg Roundabout
- Basic Turbo Roundabout
- Spiral Roundabout
- Knee Roundabout
- Rotor Roundabout
- Stretched-Knee Roundabout (3 Legs)
- Star Roundabout (3 Legs)
- Star Roundabout with four legs (asymmetric)

TUDelft

Types of Turbo-Roundabouts

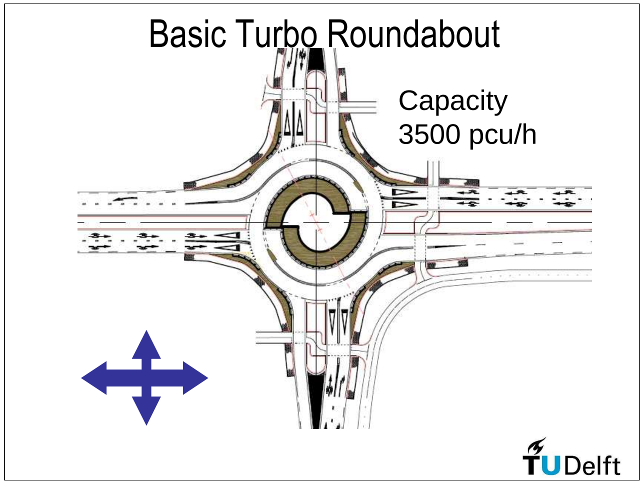
The branches of a turbo RA can have a different number of lanes, leading to several different turbo RA's.
However, for all turbo types the same key design points hold.



The main characteristics of the Egg-RA are:

- Two double lane exits and two single lane exits;
- Two double lane entrances and two single lane entrances.

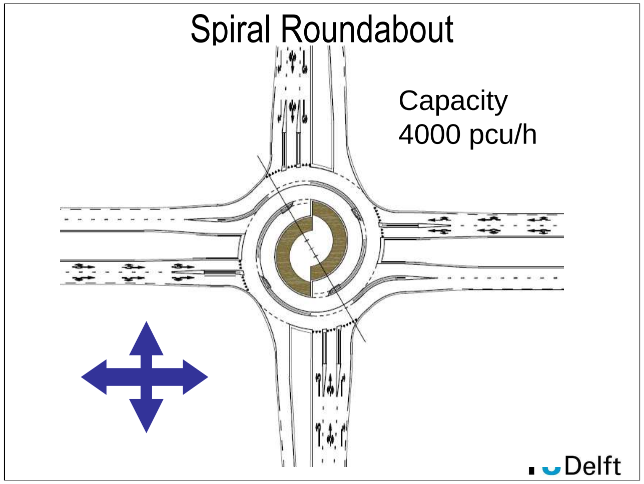
That makes this type of RA suitable for an intersection between one road with a big through going flow and the other having a relatively minor flow.



The main characteristics of the Basic Turbo-RA are:

- Two double lane exits and two single lane exits;
- Four double lane entrances.

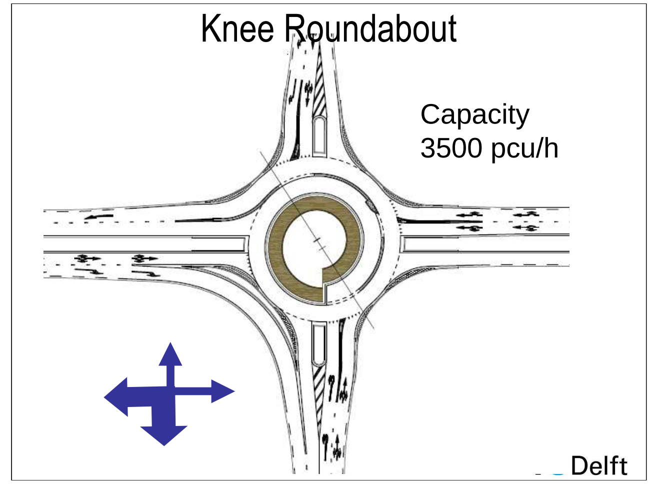
That makes this type of RA suitable for an intersection between one road with a big through going flow and the other having a somewhat less flow.



The main characteristics of the Spiral-RA are:

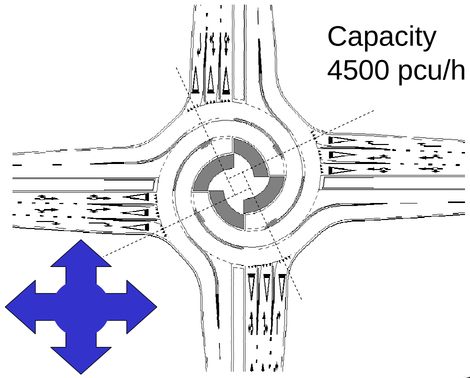
- Two double lane exits and two single lane exits;
- Two three lane entrances and two double lane entrances.

That makes this type of RA suitable for an intersection between one road with a big through going flow
and the other having a flow mainly going left and right.



The Knee Roundabout is suitable for an intersection with a dominant stream that largely goes left and right, as indicated.

Rotor Roundabout



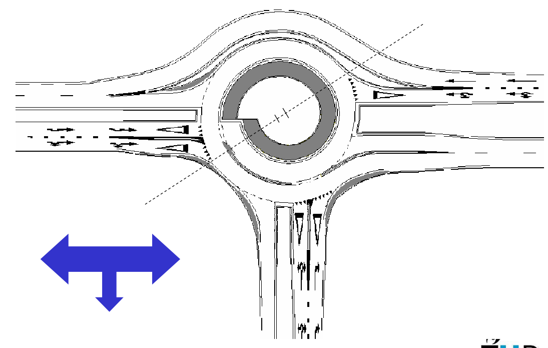
The main characteristics of the Rotor Roundabout are:

- Four double lane exits;
- Four three lane entrances;
- Possibility to turn right via two lanes;
- Possibility to go straight on via two lanes;
- Possibility to turn left via one lane.

The last point implies that the Rotor RA does not always have the highest capacity. Unfortunately it is not possible to turn left from all directions via two lanes; that would require 3 lanes on the RA in stead of 2 (and that is in conflict with the key principles of the design).

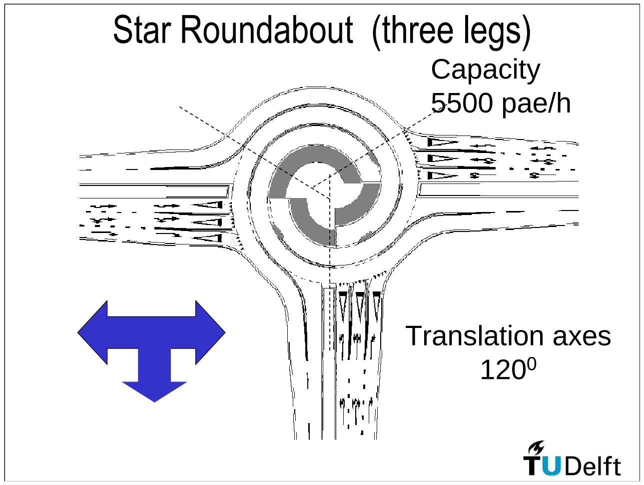
The rotor roundabout is constructed by using 4 translation axes

Stretched Knee-Roundabout



Stretched Knee Roundabout

with three branches.

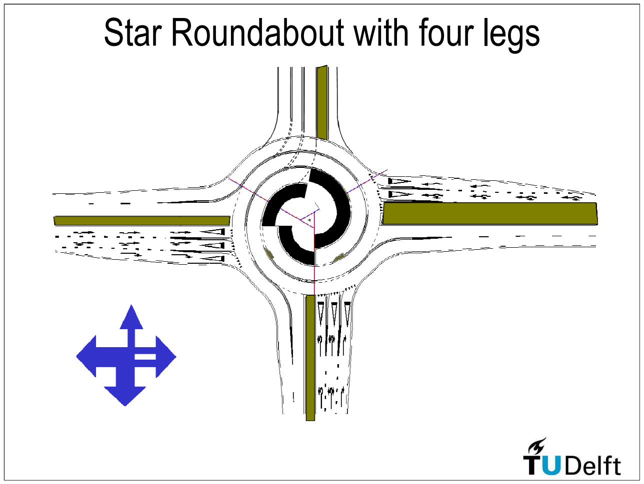


This roundabout with three legs, is called
Star Roundabout.

The translation axes make an angle of 120 degrees.

From every direction, it is possible to use two lanes for left turns.

For the legs it is necessary that the angles are 90 or 180 degrees, to keep the speeds limited.



Star Roundabout with four legs.

Principally this will be an asymmetric solution, but in some situations it will be an useful design.

Traffic Lights and Roundabouts

Possibilities?

- Full operating traffic lights will reduce the capacity of a compact single-lane roundabout.
- Full operating traffic lights will not increase the capacity of a compact two-lane roundabout.

Only four-step branch-after-branch operating system

TUDelft

What are the possibilities of traffic lights on Roundabouts?

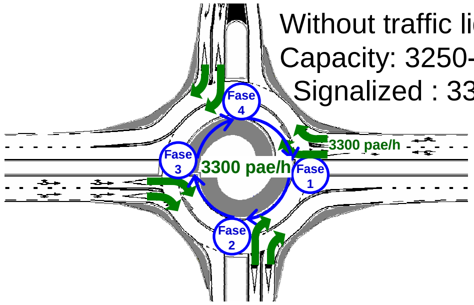
Well, it will be clear that full operating traffic lights will reduce the capacity of a compact single-lane roundabout.

But also full operating traffic lights will not increase the capacity of a compact two-lane roundabout.

The reason is: because of lack of space on compact roundabouts, only a four-step branch-after-branch operating system is usable, but not use-full.
See next slide.

Capacity signalized Turbo-Roundabout

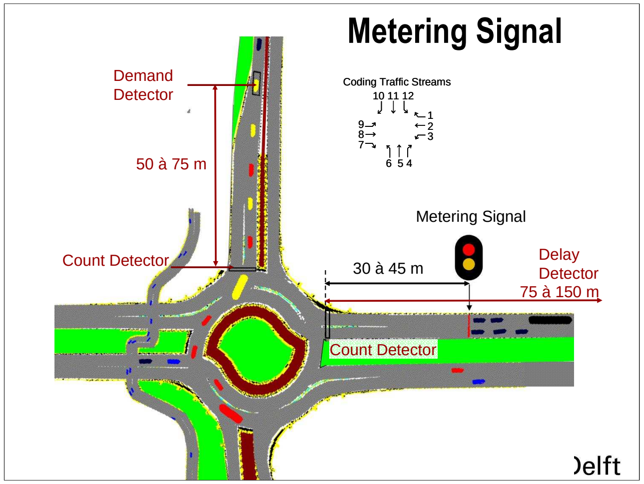
Without traffic lights
Capacity: 3250-3500 pcu/h
Signalized : 3300 pcu/h



Capacity not higher than un-signalized turbo-roundabout

When a small two-lane roundabout is signalized, the capacity does not increase, because there is not enough space for queuing on the roundabout. Only a four-step branch-after-branch operating system is possible.

(The moving–on time is rather equal to the clearance time).



Here you see the principle of a metering signal.

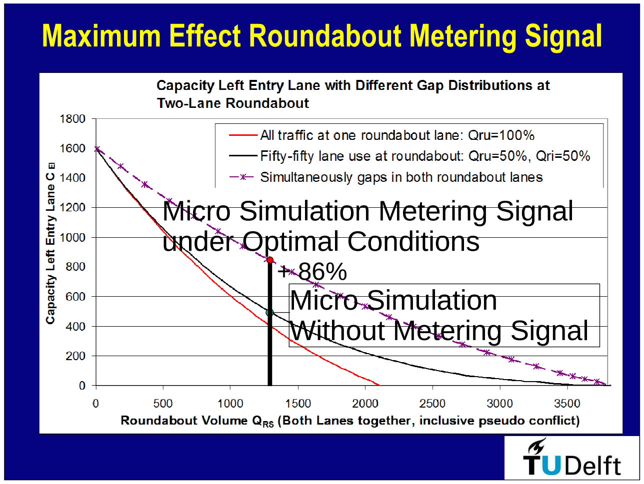
When on the north minor branch traffic is queuing, the two-light signal at the main two-lane road is activated and it will go to red via yellow.

Increase Sum Entering and Circulating Traffic

Single-Lane Roundabout			
Volume Q_R Circular Segment	100	500	1000
Entry Capacity	1550	1160	740
Sum	1650	1670	1740

Effect metering Signal

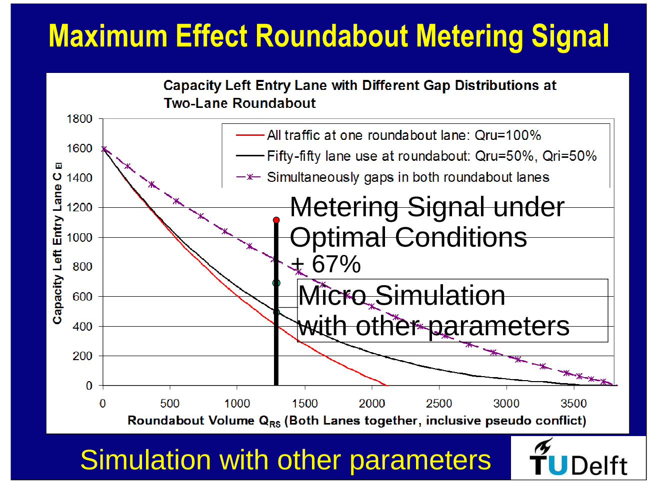
This slide shows the reason why capacity of a single-lane roundabout will not increase by applying a metering signal: a metering signal creates periods without circulating traffic in front of the overloaded entry, but in that case the total capacity of the conflict area will decrease.



We did some micro simulations for the metering signal.

We started with a very favorable flow pattern for the metering signal:
- no circulating traffic before the main entrance, and
- no circulating traffic before the minor entrance when the metering signal is acting.
Then you will find an optimal result.

In the simulation we found that the capacity of left lane of the minor road increased with 86 % from 476 pcu/h up to 864 pcu/h.

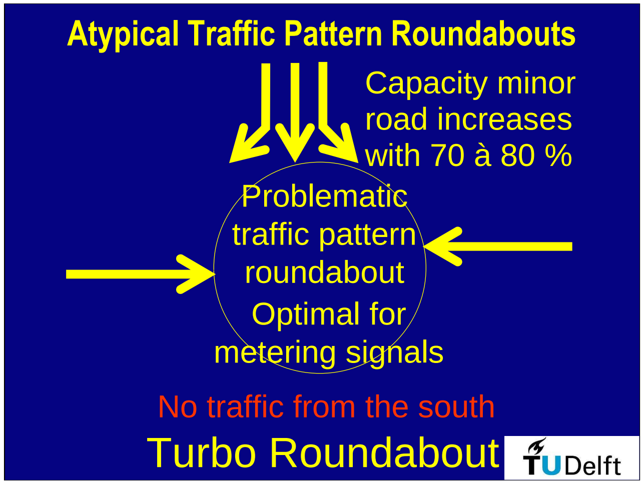


A student (Bob Granneman) did for his masters study the same with other parameters, and he found a higher capacity without a metering signal – too high when I compare it with the capacity observations we did.

Also the result with a Metering Signal was higher, but the increase was relatively less: 67% in stead of 86 %.

So, always the result you find in a micro simulation, depends on the parameters you use.

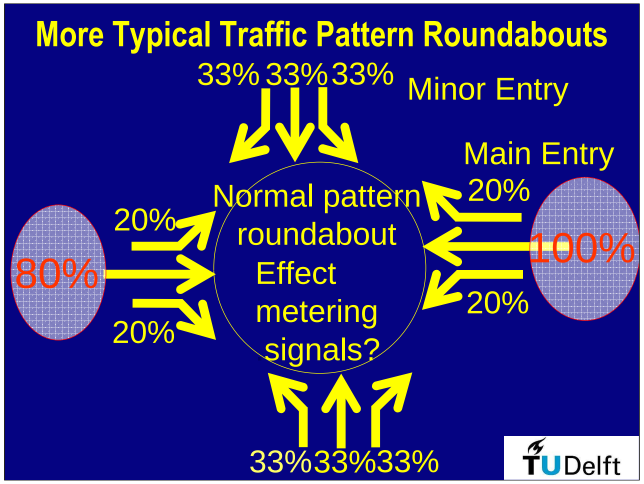
But, more important is the traffic pattern.



We used an atypical traffic pattern, without traffic opposite of the minor lane.

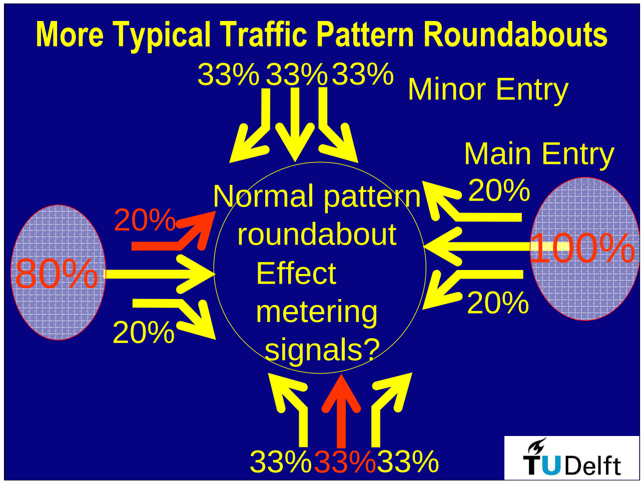
The capacity of the minor leg increased with 70 up to 80 percent.

What will be the effect of metering signalization when the traffic is queuing on the minor road with a normal flow pattern

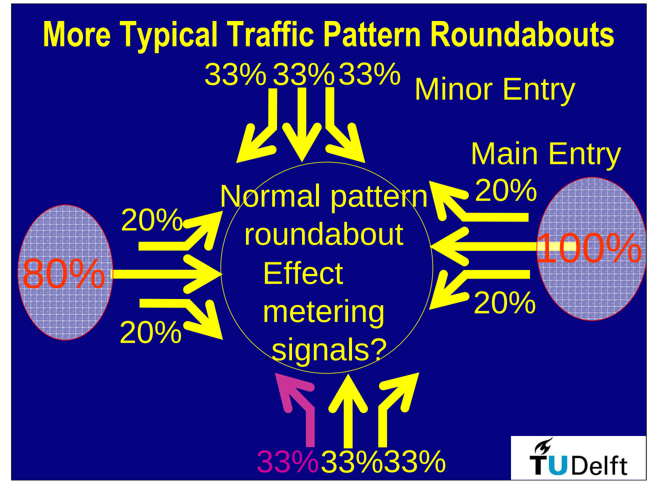


A lot of micro simulations has been done by the student I mentioned, with this basic flow pattern, by varying the proportions of the traffic from main and minor roads.

From the right the dominant traffic flow,
and the queuing traffic on the branch from the North.

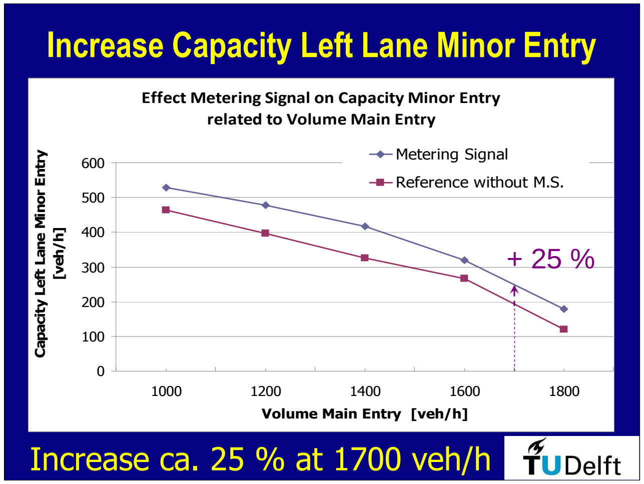


It is to understand that the traffic in the red marked directions will interrupt the main flow, so the traffic from the minor road from the North will have more opportunities to join the circulatory traffic.

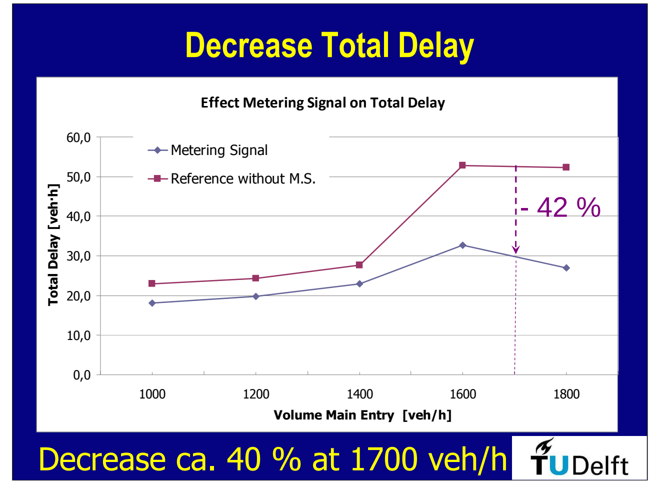


But also it is to understand, that the pink left-turn flow from the opposite direction reduces the effectiveness of the interruption of the metering signal.

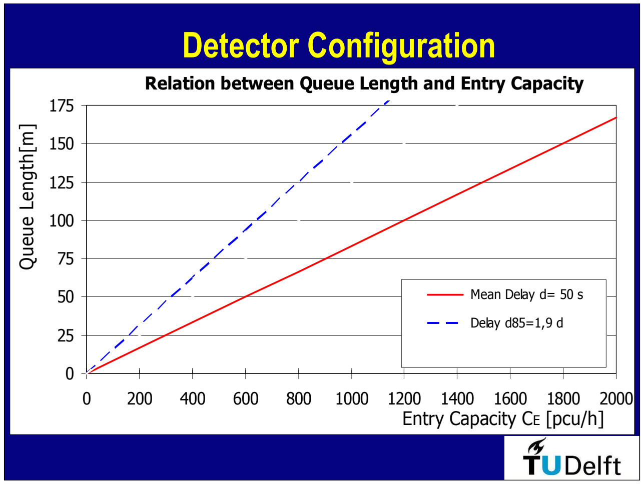
The results mentioned before, have been obtained without traffic opposite of the minor lane. So the question is: what will be the result with more usual traffic patterns?



This slide shows the results examine this question. In fact, the regarded traffic flows reduce the effectiveness of metering signals.
But still the effect is, that the capacity of the left lane of the minor entry will increase with 15 % up to 50%, depending on the volume of the main entry.
An effect of 25 % for the capacity increase of the minor leg will be a goof rule of the thump for situations with dominant main streams.



And – important – without increasing the total delay. In contrary: the total delay on all legs approaching the roundabout reduced considerably.
A decrease of about 40 percent has been measured when the volumes of the main stream was above 1600 veh/h.



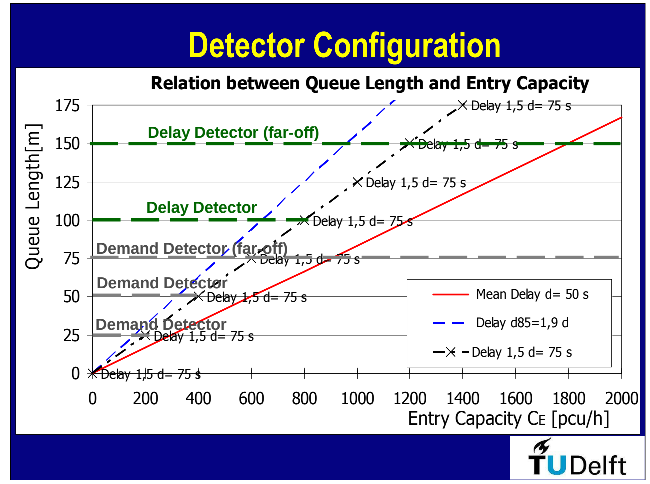
The detector configuration is important too.

In the experiments up to now, an optimal detector distance is found by trial and error.

But a more fundamental approach is required.

Then you have to realize, that the relation between queue length and delay depends on the entry capacity.

Here you see the relationship between Queue Length and Entry Capacity given a mean delay of 50 seconds (red) and the 5 percent exceeding line (blue dotted).



Suppose, we find by simulations one and a half time the mean delay of 50 seconds (the black dotted line) as a good approach for the optimum criterion to start the metering signal. Then the queue length has to be larger as the entry capacity is higher for accepting a signal from a queue detector. So the entry volume has to be measured by a count detector for deciding which queue detector has to be used (grey dotted lines).

➢The same principle holds the main branch for the detectors delaying the demand for the metering signal (green dotted lines).

Summary results Metering Signals

- Distributing waiting time more fair over the branches (if necessary).
- If applied on two-lane branches, enlarging capacity Minor Entry (15 à 45 %)
- If applied on two-lane branches, decreasing waiting time on the whole roundabout in heavy loaded situations (20 à 50 %).
- A well designed detector system is necessary.

TU Delft