Driver behaviour towards circulating cyclists at roundabouts

A vehicle simulator study with concurrent collection of eye movements

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ABSTRACT

It is a well known fact that roundabouts are safer for motor drivers than for cyclists. The main part of accidents occurs between motor vehicles entering or leaving the roundabout and circulating cyclists. In order to obtain more knowledge about why some entering motor drivers overlook circulating cyclists; the Danish Road Directorate has conducted a study of driver behaviour at roundabouts in urban areas. Is it possible to change the interaction between vehicle drivers and cyclists in relation to roundabouts by changing the design, in a way that makes it safer for cyclists? Should roundabouts be designed with or without cycle facilities? And does visibility splays have any importance for drivers overlooking circulating cyclists?

By use of a vehicle simulator together with eye tracking, a study of motor drivers' behaviour towards circulating cyclists in roundabouts in urban areas with or without cycle facilities and varying visibility splays have been conducted. A total of seven different roundabout designs with varying type of cycle facilities in the approach and in the circulation area have been tested. The seven designs have all been tested with three different visibility splays: Good, Medium and Acceptable.

The results from the analysis, indicates that visibility splays, design and the presence of cycle facilities all have influence on drivers interaction with circulating cyclists when approaching a roundabout. The results indicate that drivers are more attentive to circulating cyclists, when there is no cycle facility.

1. INTRODUCTION

The Danish Road Directorate has initiated a study designed to identify why some motorists overlook circulating cyclists when entering roundabouts *(1)(2)*. The study focuses on the coherence between driver behaviour and different designs of roundabouts with and without cycle facilities, and different visibility splays. The study is carried out as a vehicle simulator study with concurrent collection of the eye movements of the test drivers.

1.1 Background and Object

Roundabouts are generally speaking, from a road safety point of view, quite safe for road users. However the safety benefits are not as great for cyclists as for motorists. The main part of accidents with cyclists involved in roundabouts happens between circulating cyclists and motorists entering or leaving the roundabout. Different Danish studies have for a number of years tried to find out why these accidents happens *(3), (4), (5), (6)*. The results of these studies points to several parameters that can have an effect. Further studies are still needed, studies that can contribute new knowledge on motorists' interactional behaviour. This can hopefully help explain why these accidents happen and how to minimise the number of them in the future.

In light of this, the Danish Road Directorate has initiated a study of road user behaviour between motor drivers entering the roundabout and circulating cyclists with the purpose to improve the road safety for cyclists. The behaviour of motor drivers is evaluated on a basis of a number of measurable behavioural factors. The factors are primarily based on motor vehicle speed, vehicle position in relation to cyclists plus motor drivers visual gaze against circulating cyclists. The measured behavioural factors are connected with roundabout design and visibility splays. The study is carried out as a vehicle simulator study, in cooperation between the consulting company Trafitec, the Norwegian Research Institute SINTEF and the Road Directorates in Denmark and Norway.

2.0 VEHICLE SIMULATOR AND EYE TRACKING

The vehicle simulator is based on a full scale and fully equipped Renault Scenic 1997 model with a 3-axis motion system and a car body vibration system. 5 channels of visual information provide the field of view. The steering wheel is equipped with a torque motor to give force feedback. The simulated traffic scenarios include autonomous cars capable of acceleration, braking, steering, and over taking vehicles.

The size of each screen is 2.4 meter tall and 3.1 meter wide. The resolution of the visuals is 1024 x 768 pixels. The three front screens are rear projected and provide in sum a 180 degrees horizontal field of view and a 47° vertical field of view. The two screens behind the vehicle are front projected and supply in sum a 90° vertical field of view and a 47° vertical field of view each (see figure 1).

FIGURE 1 Vehicle simulator. The field of view makes it possible for test drivers to see the road from the windscreen, rear-view mirror and side-view mirror, and in an angle of 45 degrees to each side.

2.1 Data logging

Log files from the simulator provide registration at 20 Hz rate of relevant variables such as: Position (x,y,z); Speed; Use of Pedals: Brake, accelerator and clutch; Parking brake; Steering wheel angle; Gear choice; Lateral position on road and Distance to other vehicles.

2.2 Video camera and recording

The car simulator uses three cameras to record what happens while driving. One camera captures the visual scene (forward direction), one camera captures the drivers face, and one is mounted on the inside of the roof, behind and to the right of the driver capturing the instrumentation of the car and the driver’s hands. All cameras are fused together, with a separate stream from Smart Eye (explained below), using a video multiplexer resulting in one picture, containing four smaller video streams. Subtitles are added to the video, by use of a graphics superimposing unit controlled by the Videotext PC. The subtitles may be configured to show data on users demand. Standard data are date, time, speed and frame. See figure 2.

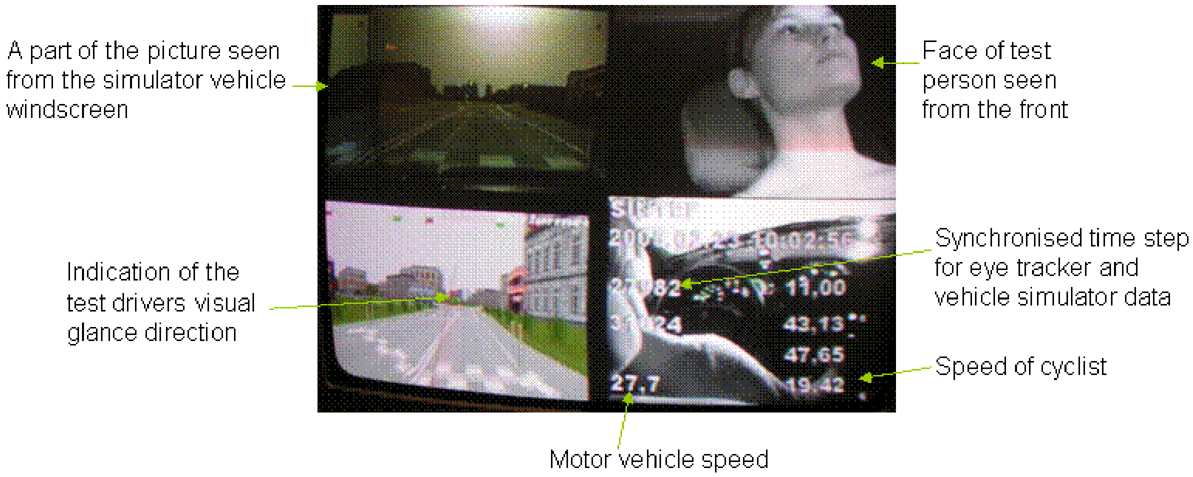


FIGURE 2 Example of video recording of test drive. The four pictures are synchronised.

Sound is provided by a four-channel high fidelity sound system with loudspeakers inside the cabin and a subwoofer in the trunk. The system provides sound from the driver's vehicle as well as from other vehicles.

The benefits of the vehicle simulator is that it is possible to vary the single parameters, and at the same time to be in control with the different variables. In this way it is possible to ensure that test drivers are driving through the road net at the same conditions.
The disadvantage of simulation is in part, that is the car lacks the movements associated with acceleration and deceleration. Also the fact that the scenarios are an animation is sometimes a disadvantage. Several test drivers' experienced "Simulation sickness", because they felt that the projection of the animation flickered.

2.3 Eye tracking

Eye movement is an important experimental technique, in the analysis of visual orientation and attention, in relation to identification of road-user's search and decision making strategies while driving. Eye movements give an indication of the focus of visual attention. The link between eye movements and attention is strong and provide us with information of road user's thought process *(7)*.

Driver's visual attention is registered as the object where her or his gaze is pointed. The gaze indicates the test drivers focus and visual attention – but does not say anything about whether or not the person actually understands and uses the information of what they are looking at. Equally it is not possible to say anything about what the road user actually sees or understands in his or her periphery field of vision.

The eye tracking was implemented by the Swedish system SMART EYE. The system consists of three cameras placed on the dashboard in the vehicle simulator, see figure 3. In this way the test drivers does not notice the eye tracking while driving. The system has a frame rate of 25 frames per second.

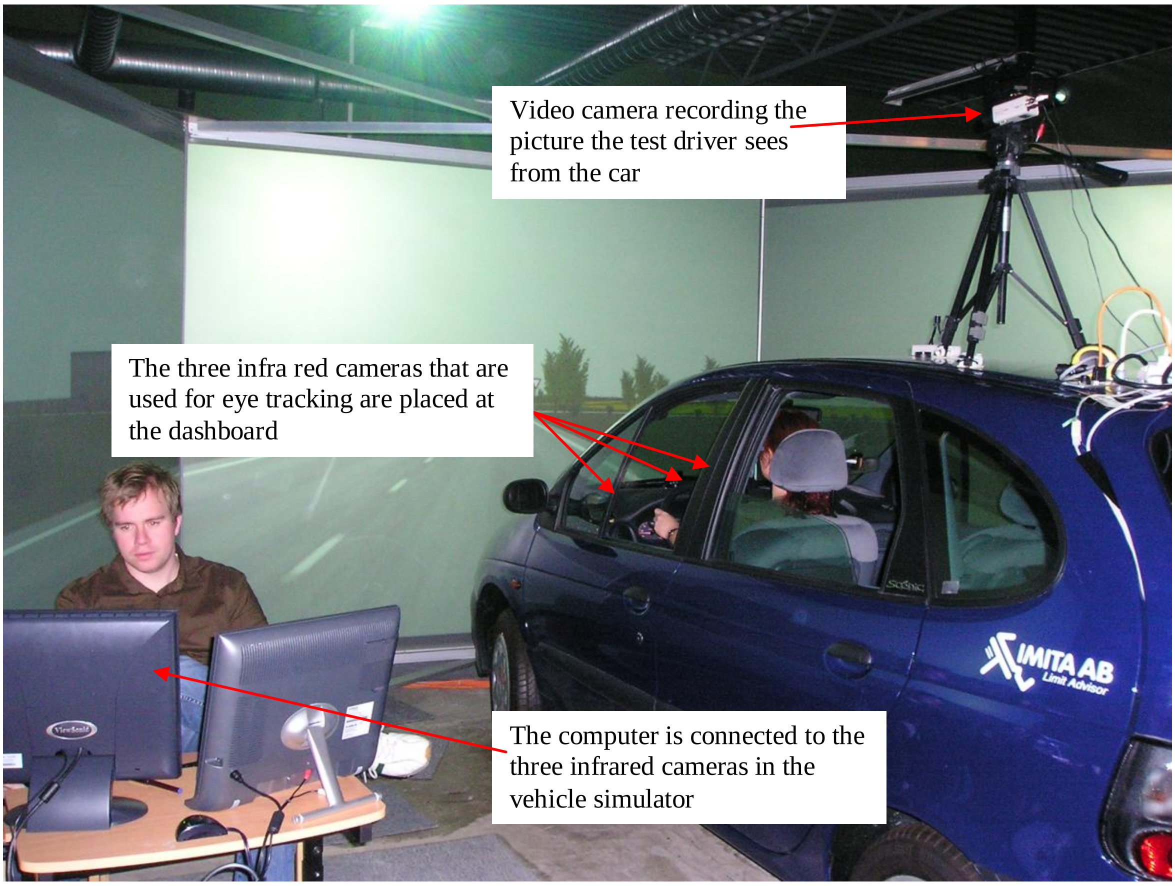


FIGURE 3 The research set-up of eye tracking. The eye tracker consists of three infrared video cameras recording the face of the test driver during the test. The cameras are placed on the dashboard and connected to a computer, which amongst other things renders a computation of the test driver's visual focus.

In order to calibrate the eye tracker, a personal profile for each test driver has to be completed before the test driving begins. The personal profile is made up of a group of frames, from a video recording, with a number of facial features like nostril, eyelids, eyebrows and mouth corners marked in each frame. These marked pictures are used to build a model of the head and eyes, see figure 4. The marked features are used as a template for the computation, when performing tracking. Before each test drive a gauging of the system is carried out, to set it up for the individual that is about to drive.

When the study took place, automatic analysis of eye tracking should have been possible, but the there were and are still many limitations of the system, so it was decided to do the analysis of eye gazing manually by going through the video recordings and looking at them *(8)*. Only glances with duration of 2 frames or more is considered as a meaningful glance.

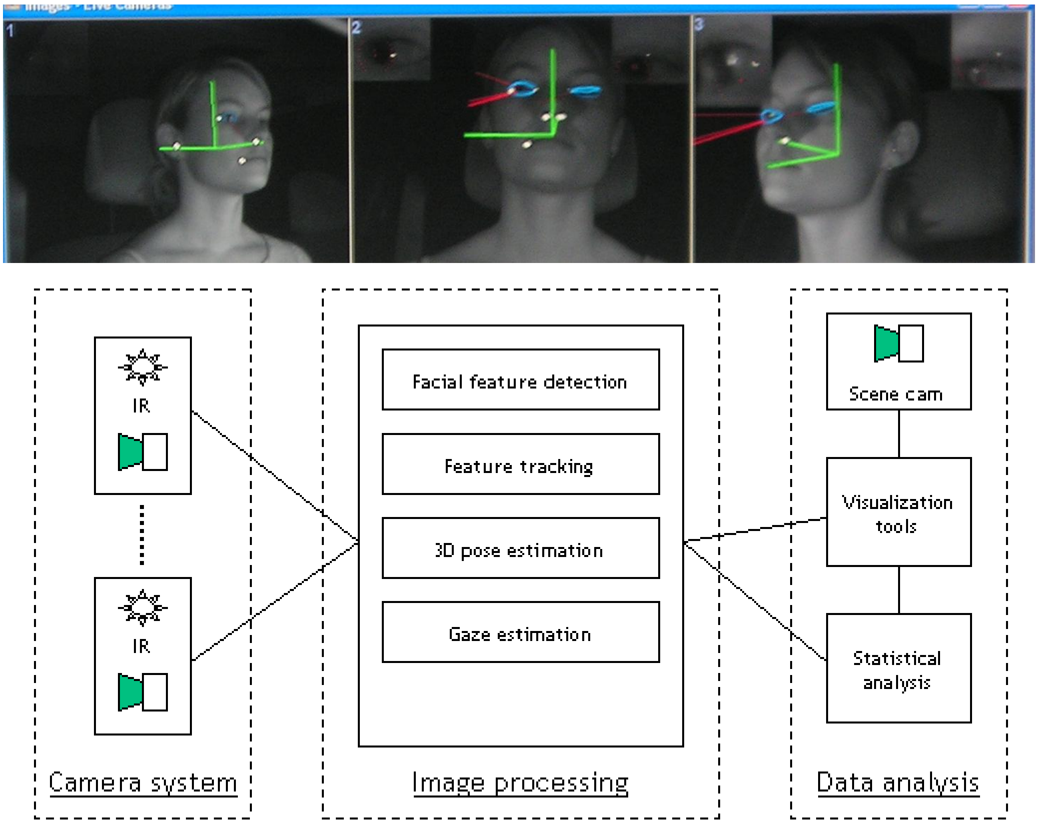


FIGURE 4 Process sketch of the eye tracker. By identifying a number of land markings on the test driver's face (here eyes, mouth corner, nostrils and earlobes) and matching these to points in the 3D computation of the driver's head, a calculation of the orientation and positioning of the subjects eye can be made with great precision. The 3D model can then place the eye's iris and pupil again and determine the direction of the gaze.

3.0 RESEARCH SET UP

Three databases containing a 3-D model of the road network were specifically designed for this project. The databases are based on video recordings, photos and drawings of Danish roundabouts, all designed in accordance with the Danish Road Standards and Guidelines *(9)*.

To make the driving as realistic as possible, the network consisted of other types of crossings than roundabouts. Between the crossings are placed buildings and plantation, and during the test other simulated vehicles drives through the road network in a random order. Furthermore three visually different (with different clothes) simulated cyclists were designed specifically for this study.

3.1 Description of the 21 studied roundabouts

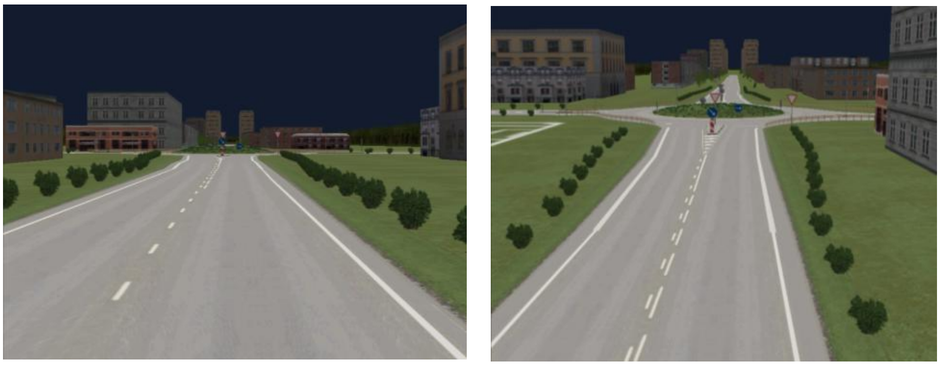
The study includes seven basic roundabouts with different designs. Four designs (1-4) with cycle facilities and three designs (5-7) without cycle facilities see table 1. All seven basic roundabouts are tested with respectively Good, Medium and Acceptable visibility splays, corresponding to at total of 21 roundabouts, see table 1.

TABLE 1 Definition of roundabout designs, and numbering of the 21 roundabouts included in the study.

Roundabout design and numbering of the 21 roundabouts	Visibility splays		
	Good	**Medium**	**Acceptable**
Roundabout design 1: Cycle track in the approach and circulation area	1	8	15
Roundabout design 2: Cycle track in the approach, blue cycle lane in the circulation area	2	9	16
Roundabout design 3: Cycle track in the approach and circulation. Orange fence in the circulation area between the roadside and the pavement	3	10	17
Roundabout design 4: Cycle track in the approach, hump in the approach and cycle track in the circulation area	4	11	18
Roundabout design 5: No cycle facility in the approach, no cycle facility in the circulation area	5	12	19
Roundabout design 6: No cycle facility in the approach, no cycle facility in the circulation area, orange fence in the circulation area between the roadside and the pavement	6	13	20
Roundabout design 7: No cycle facility in the approach, hump in the approach, no cycle facility in the circulation area	7	14	21

The visibility splay is varied by changing the plantation of the land area and the height of the central island, se figure 5. For all roundabouts, the buildings remain unchanged the last 150 m before the roundabouts “give way” lines while the plantation varies to change the visibility splays. But the surroundings, buildings and plantation, on stretches between the roundabouts differ. Cycling in the roundabouts circulation area is permitted. All roundabouts are situated in urban areas with a signed speed of 50 km/h (31 miles per hour). Roundabouts containing a blue lane or an orange fence are expected to make cyclists more visible, while hump is expected to make car drivers reduce their speed when driving towards the roundabout.

Example of roundabout with good visibility splays. No plantation in the approach. Height of the central island is 1.0 m with the plantation included.



Example of roundabout with medium visibility splays. Height of the central island is 1.5m with the plantation included. Height of bushes on the approach are 0.8 m.

Example of roundabout with acceptable visibility splays. Height of the central island is 1.9 m with the plantation included. There are trees on the approach with an individual distance of 6 m.

FIGURE 5 The three different visibility splays

3.2 Roundabout design with and without cycle facilities

As described earlier this study includes both roundabouts with and without cycle facilities. The designs are as equal as possible. Radius of the central island (12.5 m) and the width of the road lane (5.0 m) is the same in all roundabouts. For roundabouts with cycle facilities the width of the cycle track is 2 m. This design difference means that the location of the conflict point is slightly staggered from each design, see Figure 6. For roundabouts without cycle facility one can imagine that the interaction between cyclist and car driver will be more smoothly than for roundabouts with cycle facilities, where the conflict point is situated immediately after the car driver pass the give way line.

The difference in design also means that the angle at which the car driver can see the cyclist differs in the two designs. This difference is probably of less importance when the road users are far away from the conflict point and increasing importance as the road user comes closer to the conflict point.

The majority of the test drivers regulate their speed after the cyclist's position in the circulation area. This means that almost none of the test drivers come to a full stop before entering the roundabout.

On figure 6, is a plot of driving paths for road users in roundabouts with and without cycle facility. The plots are based on the test results. There is no apparent difference in the car driver's choice of path, when comparing roundabouts with and without cycle facilities. The location and angle of the "give way" line differs slightly for the two designs. The angle of the "give way" line is expected to be of some importance for car drivers stopping at the "give way" line, and almost of no importance for car drivers who enters the roundabout without stopping at the give way line.

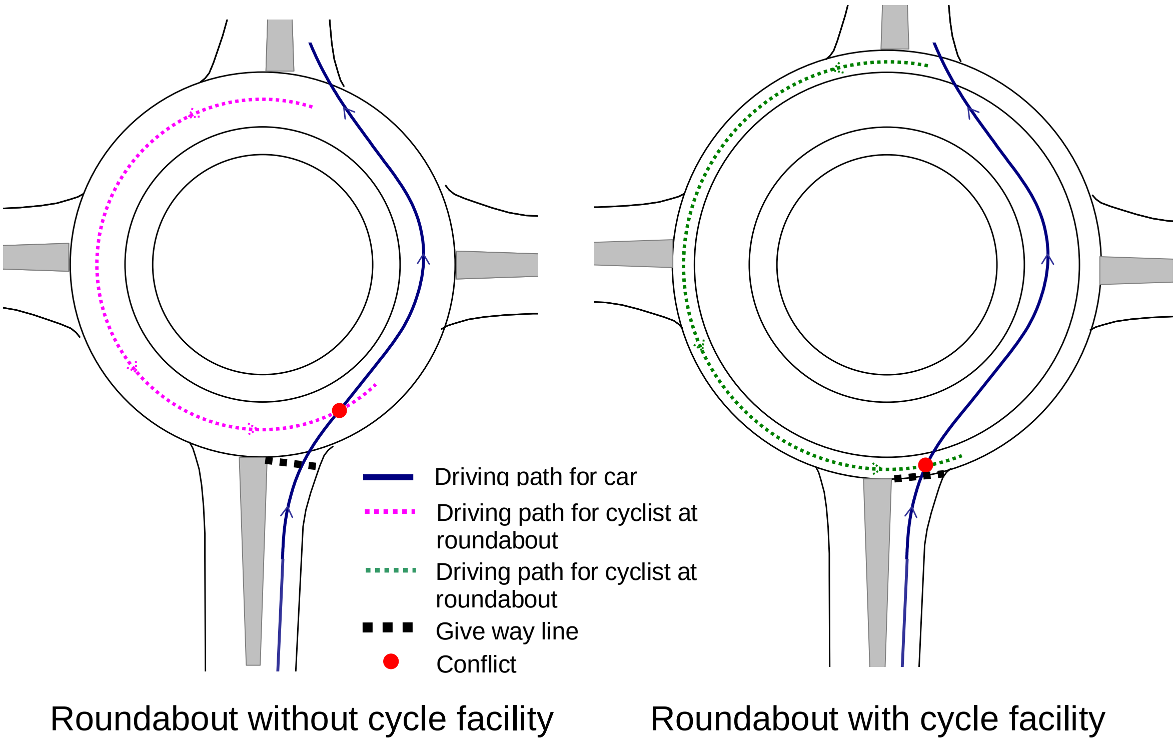


FIGURE 6 Specification of driving paths for cyclists and cars, and indication of placement of conflict points and give way lines.

3.3 Design of scenarios

In this study, the focus has been on one scenario where a motor driver approaches the roundabout while a cyclist is circulating in the roundabout, and a possible conflict can occur. There are no other road users present in the analysed situation.

Since other simulated vehicles drive through the network in a random order test drivers never know when or where other road users will appear. This also means that situations where other simulated cars are present when the test driver enters the roundabout are excluded from the final analyses.

The scenario has to ensure that the conditions are as uniform as possible for the test drivers. To ensure that test drivers with a certain possibility have to make an interaction with an circulating cyclist when entering the roundabout the start time of the cyclist depends on the speed of the test driver in a distance of 180 m, 160 m or 120 m from the give way line. The point where the cyclist for the first time enters the test driver's field of vision depends on when the cyclist starts driving and the test drivers' choice of speed in the approach. At roundabouts with cycle facilities the cyclist rides in the middle of the cycle facility and in roundabouts without cycle facilities circulating cyclist's rides in the middle of the road, see figure 6.

3.4 Test drivers

Other research has shown that the number of test drivers in this type of study is of less importance than the number of rides through the single roundabout *(10).* In this study we had 18 test drivers with a Danish driver's license. Each person drove through the 21 roundabouts once or twice. In cases where test drivers drove through the roundabouts twice it took place over two days. Test drives where the driver experienced "Simulation sickness" are not included in the results of this study. Test drivers were told that the purpose of the project was to test new equipment.

3.5 Registration of parameters

Test drivers' adjustments to circulating cyclist are measured in terms of approaching speed, eye gazing and time distance to the point of conflict.

A description of the parameters used in post-analysis, along with the expected impact they will have on road safety, follows below.

Speed profile:

The speed profile for test drivers is measured from 150 m away from the give way line in the approach up to 50 m after leaving the circulation area in the roundabout. From this profile it is possible to see the actual speed at specific areas e.g. when entering and leaving the roundabout. It is important that the test driver aims for full control of the car, which involves a steady speed adaptation in the approach with no strong braking or acceleration.

Time distance in point of conflict:

The time distance between test drivers and bicycle at the point of conflict is defined as the time from the first road user leaves the point of conflict to the next arrives, see figure 7.

The time distance indicates how close the road users are passing each other in the conflict point, and how long time they have to react to each other, if an unexpected situation should occur. Especially events with a short time distance in the conflict point are interesting because it is in these specific situations that the potential for conflicts/accidents are largest.

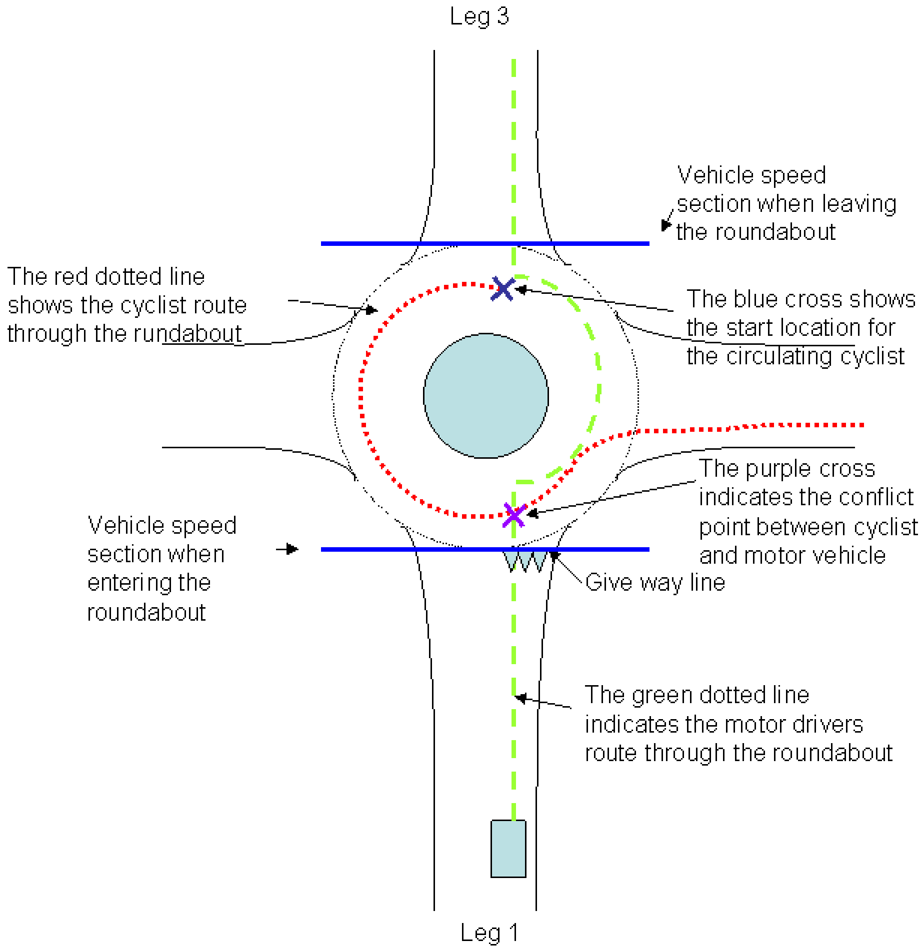


FIGURE 7 The Observation area starts 150 meters before the give way line (leg 1) and continues up to the point where the test driver leaves the roundabout (leg 3). The purple cross indicates the conflict point between the circulating cyclist and the entering motor vehicle.

Eye tracking:
Motor drivers visual attention to circulating cyclists is registered by looking at their eye movements. How long is a motor driver looking at the cyclist compared to the time the cyclist is in the driver's field of vision. Furthermore the time from when the cyclist appears in the drivers vision field to the first time the driver has the first direct gaze pointed at the cyclist (detection time) is also registered. The detection time depends; probably to a great extend, on whether or not the car driver needs the information. The cyclist should be detected from a proper distance from the roundabout judged by the actual traffic situation, including vehicle speed, vehicle distance from the roundabout and also speed and location of the circulating cyclist.

Number of glances against the circulating cyclist
This parameter is difficult to interpret. Does the driver see the cyclist when his or her gaze is directed at the cyclist? How attentive is the driver with a single glance? That is also unknown. The number of glances at the cyclist probably depends on the driver's judgement of the present situation; including how safe or unsafe the situation is deemed to be by him or her. The more unsafe the situation, the more glances. Whether the number of glances can be related to the present perceived road safety, depends on when in the course of the test, that the driver directs his or her gaze to the cyclist. The driver should have at least one and preferably more than two glances at the cyclist. One of the glances should be at the point where the cyclist and/or the car arrive at the point of conflict. This can also be coupled to the amount of time the driver should be focusing on the cyclist, also in relation to the time distance in the point of conflict.

From a road safety point of view, it can be assumed that it is an advantage if the driver has greater visual focus on the cyclist, the closer he is to the point of conflict. And thus is more attentive to the cyclist and his or her relative position, just before the car enters the roundabout. A disadvantage of using the driver's eye movements as a behavioural parameter is that, as previously mentioned, it is not known whether or not the driver has seen or recognized the object that his or her glance is directed at. In this study, the drivers had, on average, 3 to 5 glances at the cyclist and in every test run they had a minimum of 1 glance at the cyclist.

Because of the enormous amount of data it was decided to divide glances into only two groups; glances against circulating cyclists, and all other glances.

4.0 RESULTS AND CONCLUSION

The results from the analysis, indicates that visibility splays, design and the presence of cycle facilities all have influence on drivers interaction with circulating cyclists when approaching a roundabout.

The analysis shows that the speed profiles are very much alike regardless of roundabout design and visibility splays. The speed profiles shows that drivers at all times realize they are reaching a roundabout, and reduce the vehicle speed as they reach the roundabout, see figure 8.

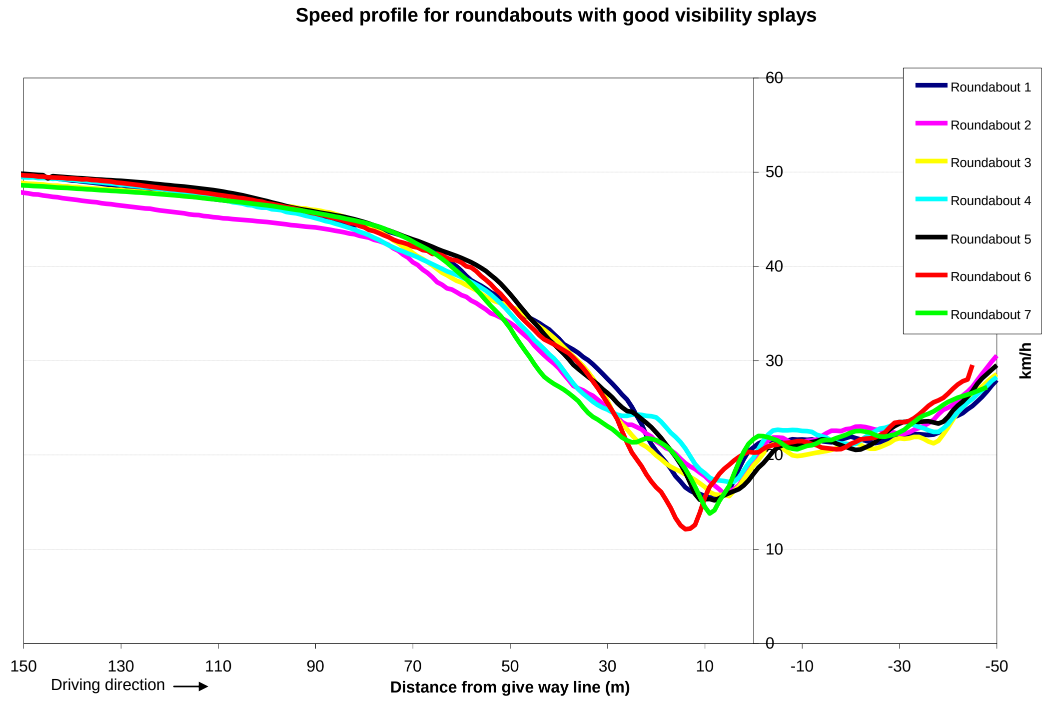


FIGURE 8 Speed profiles for roundabouts with good visibility splays.

When comparing the four different roundabout designs with cycle facilities (design 1, 2, 3 and 4) with the three designs without cycle facilities (design 5, 6 and 7), the results indicates that driver behaviour is more consistent for roundabouts without cycle facilities, see table 2. The average time distance at the conflict point is significantly smaller for roundabouts without cycle facilities and the variation is less than for roundabouts with cycle facilities. Although the time distance is lower for roundabouts without cycle facilities it is not critical low. The test driver's speed at the point of conflict is less than 30 km/h, and the time distance is still sufficient to assume that the drivers have the situation under control.

TABLE 2 Main results for roundabouts with and without cycle facility. * indicates that the difference is significant.

	Cycle facility	
	With	Without
Speed at entry line	18-21 km/h	18-22 km/h
Speed when leaving the roundabout	22-27 km/h	22-26 km/h
Time distance in conflict point	3.3 sec*.	2.8 sec*.
Detection time	3.1 sec.*	2.5 sec*.
Part of time test driver looks against circulating cyclist	17%*	21%*
Distance from give way line, where test drivers have the largest visual focus against the circulating cyclist	10-40 m	9-13 m

Test drivers detect cyclists earlier at roundabouts without cycle facilities and the share of time they look against the circulating cyclist are higher. There is no evident that test drivers detect cyclists earlier at roundabouts with blue cycle lane or orange fence (design

2, 3 and 6) compared to the other roundabout designs. It is not known whether or not drivers who spot cyclists earlier, remember and use the information as they approach the roundabout.

Car drivers' visual attention on cyclists is larger for roundabouts without cycle facilities, and also the detection time is smaller, both differences are significant. For designs without cycle facilities drivers have the greatest visual attention on cyclists in a distance of 9-13 m from the give way line. For designs with cycle facilities drivers have their maximum attention against cyclists 10-40 m from the give way line. From a road safety point of view, one can assume it is an advantage if car drivers have the greatest visual attention relatively close to the point of conflict, and are then probably aware of the position of the cyclist immediately before entering the roundabout. An example of a combined speed- and eye tracking profile is illustrated in figure 9.

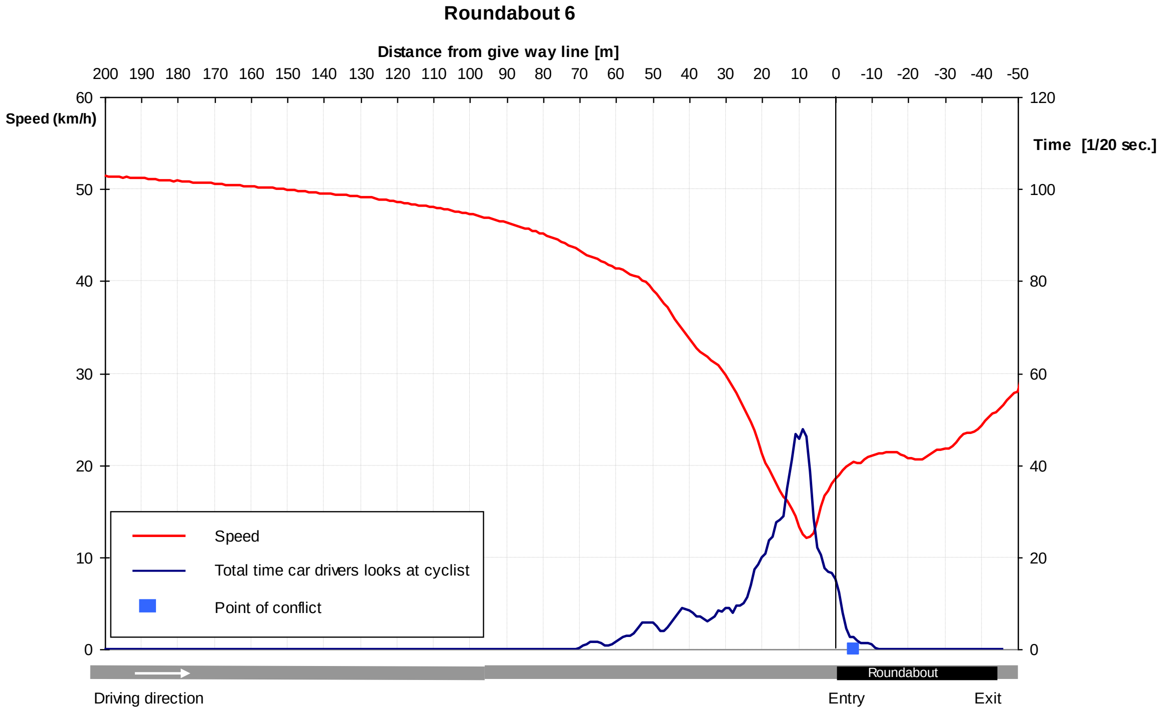


FIGURE 9 Example of combined speed and glance profile for roundabout design 6. It clearly shows that the test drivers had the greatest visual focus on the cyclist at a distance of 10 meters from the give way line. The drivers' minimum speed on the approach is 12 km/h at a distance of 8 meters from the give way line.

The drivers spot the cyclists significantly earlier in roundabouts with good visibility splays, in contrast to roundabouts with medium and acceptable visibility splays. The time distance is also significantly lower for roundabouts with good and medium visibility splays, than for roundabouts with acceptable visibility splays. The variance of data is also lowest for roundabouts with good and medium visibility splays. The combined amount of time that is spent looking at the cyclists is apparently independent of visibility splays. See table 3.

TABLE 3 Main results for roundabouts with different visibility splays

	Visibility splays		
	Good	Medium	Acceptable
Speed at entry line	20-22 km/h	18-22 km/h	18-22 km/h
Speed when leaving the roundabout	23-27 km/h	23-26 km/h	22-26 km/h
Time distance in conflict point	2.9 sec.	3.0 sec.	3.3 sec.
Detection time	2.5 sec.	2.9 sec.	3.0 sec.
Part of time test driver looks against circulating cyclist	19%	18%	18%
Distance from give way line, where test drivers have the largest visual focus against the circulating cyclist	9-20 m	11-27 m	10-40 m

All together the results suggest that drivers are more attentive to circulating cyclists, when there is no cycle facility. This combined with the fact that the behaviour of the drivers is more regular in roundabouts with no cycle facility, implies that the road safety in these roundabouts must logically be better than in roundabouts with cycle facilities. German and Dutch accident studies points in the same direction. They also indicate that the number of accidents with cyclists involved is higher for roundabouts with cycle facilities *(11)*.

It is not possible to determine if there is any road safety difference on the 7 designs that where studied, with the available data. This means there is no indication that humps or the like have any effect on how drivers behave, at least not in a road safety perspective. Likewise there is no indication that orange fences or blue cycle lanes in the circulations area make drivers more attentive to circulating cyclists.

It should be pointed out that this study only focuses on a situation where there is one driver and one circulating cyclist in the observation field at the same time. If one wishes to focus on more complex scenarios, where there are more road users present at the same time, the impact of the individual parameters along with the effect they have on each other, could conceivably be different.

This study does not make it possible to say anything about whether one type of cycle facility is safer than another, from a road safety point of view. However one should bear in mind that we only look on a very limited traffic scenario. If the traffic situation is more complex with more road users at the same time, the road user behaviour and interactions will probably be very different.

The results in this analysis are built on behavioural studies of car drivers in roundabouts with one entry and one exit lane and one lane in the circulation area. It is a simulator study, which means that the traffic situation is limited in variation and does not give the same complexity as studies in real traffic.

This study has produced new knowledge of road user behaviour when driving in and through roundabouts. But more information on how to interpret road user's visual attention is still needed. Do motorists see and recognize what they look at, and how do motorists adapt their visual search when approaching a roundabout. Last but not least, how can we use this knowledge to improve road safety?

In the light of the results of this study, an attempt is made to set up a table that gives a cautious estimate of the investigated parameters influence on road safety (and not the definitive truth).

TABLE 4 Cautious estimate of investigated parameters expected influence on road safety. + indicates a good road safety and – a low road safety.

Parameters	Low value	High value
Speed at entry line (depends of the present traffic situation)	+ (0-30 km/h)	- (>30 km/h)
Speed at exit (depends of the present traffic situation)	+ (0-30 km/h)	- (>30 km/h)
Time distance in conflict point	- (<1,5 sec.)	+ (>2 sec.)
Numbers of glances against cyclist	- (<2)	+ (≥ 2)
Share of time with visual attention at cyclist (last 4 sec. before the cyclist arrives at the conflict point)	-	+
Distance from give way line where car driver has the greatest share of visual attention on the cyclist. (depends on the road users location in relation to each other)	+	-
Detection time	(+)	(+/-)

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