

# Evaluation of signalised high-volume multi-lane turbo roundabouts: road scene analysis, road user survey, and video-based analysis of road user behaviour

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## Abstract

The Province of Zuid-Holland has introduced the signalised high-volume multi-lane 'Turbo roundabout' as a new intersection lay-out with the most important characteristic that there are physically separated driving directions, in contrast to conventional roundabouts. TNO evaluated two existing signalised turbo roundabouts with respect to traffic flow and road users' behaviour and experience. The evaluation of road users' behaviour and experience consisted of a road scene analysis by two human factors experts, a behavioural analysis based on video recordings and a road user survey in the direct vicinity of one of the turbo roundabouts. For each turbo roundabout, eleven hours of digital video recordings were analysed for error manoeuvres and other deviant behaviour for each approach branch.

The road scene analyses indicate that, in general, at both turbo roundabouts, maximum effort is devoted to carefully indicating possible destinations before road users enter the roundabout. The route signing is uniformly and consistently designed with the same destinations on the pre-direction sign panels and on one main gantry sign panel. Roundabout arrows painted on the road surface are uniformly indicated on the gantry panel just in front of the turbo roundabout. Once one has passed the gantry sign, however, no further route directions are presented, neither on negotiating or leaving the roundabout. The video-based behavioural analyses indicate that, on average, 15 error manoeuvres/hour occurred at the turbo roundabouts. The filtering during the approach of the turbo roundabouts is conducted rather smoothly. In line with the outcome of the road scene analyses, on both roundabouts the left-turn manoeuvre appears the most problematic one. Turning left directly beyond the first traffic light was considered to be the most serious problem because one enters the roundabout against the driving direction (ghost riding). While on the roundabout, the path choice for left-turning traffic at the second traffic signal stands out most prominently. Complex error manoeuvres (several times a carriageway switching on the roundabout resulting in at least one complete round) indicate that one does not know where to go to or that one loses the right path choice completely. From the survey results it can be concluded that the interviewed road users are reasonably positive about the signalised turbo roundabout, but they indicate that habituation is very important. A lot of road users admitted that when the situation was new, they made several mistakes

(wrong traffic lane choice). Many respondents also indicate that they frequently see other road users make similar mistakes.

On the one hand, approaching and negotiating signalised turbo roundabouts appear to be a complicated manoeuvre, especially for the less familiar road user. We expect that recommendations for improving the lay-out and outfit of a signalised turbo roundabout (we made some) will reduce the number of error manoeuvres, but not exclude these fully. On the other hand, the traffic throughput analysis reveals a much higher capacity of a signalised turbo roundabout than of a conventional signalised intersection, but at a cost of a higher number of red runners. Based upon the results of the behavioural study and the road user survey, we recommend to be careful in applying this type of intersection, and only consider application if the traffic capacity for heavy crossing flows really requires so.

## 1. Introduction

Figure 1: Overall picture of the turbo roundabout Doenkadeplein.



In 2000, the Province of Zuid-Holland has introduced the at-level signalised high-volume multi-lane 'Turbo roundabout' as a new intersection lay-out and realised two signalised turbo roundabouts, the "Doenkadeplein" since half 2006, see Figure 1, and the "Tolhekplein" in July 2007. Due to increasing traffic demands, increasing road capacity is needed on the provincial network. Roundabouts and non-signalised turbo-roundabouts are proven intersection types for a safe traffic performance, but for situations with a higher capacity demand other intersection solutions are needed. Signalised intersections offer higher capacities but display a much higher accident risk than roundabouts. Signalised turbo roundabouts may combine higher capacity with better safety performance and may fill the gap between roundabouts and grade-separated intersections. Design principles for the signalised turbo roundabout can be found in Fortuijn and Carton (2008).

Commissioned by the Province of Zuid-Holland, TNO evaluated the two existing Turbo roundabouts with respect to traffic flow (together with Royal Haskoning) and road users' behaviour and experience. For the evaluation of traffic flow, the traffic throughput at turbo roundabouts has been compared with that of a conventional signalised intersection. Mainly due to the two-phase control at the turbo roundabout, the cycle times at the signalised turbo roundabout are considerably shorter than at the signalised intersection, result in shorter waiting times, in shorter delays for left-turning traffic, and in more favourable waiting queues. For more details about the traffic flow results, the reader is referred to Horst, et al. (2008). The evaluation of road users' behaviour and experience consisted of three parts: a

road scene analysis by two human factors experts, a behavioural analysis based on video recordings and a road user survey in the direct vicinity of one of the roundabouts.

### **1.1 Road Scene Analysis**

Two human factors experts from TNO with knowledge of human functioning in road traffic, human information processing and decision making, have carried out a road scene analysis at both signalised turbo roundabouts. The purpose of the road scene analysis is to identify specific design elements that may contribute to hesitating or unsafe behaviour, traffic conflicts, and the like. From a road users' perspective, for each branch of the turbo roundabouts, the experts make an inventory and a judgement of what a road user encounters while approaching and negotiating the roundabout and how that may influence the behaviour and decision making at a given place and a given moment in time. This judgement is based on their own driving experience while approaching and negotiating the roundabouts from all directions, and a fine-tuning afterwards by replaying a video and observing various pictures made while driving.

### **1.2 Road user behaviour**

At each signalised turbo roundabout, digital video recordings were made by means of three video cameras unobtrusively mounted in existing public lamp posts. For each turbo roundabout, video recordings have been made for a period of three days. From this a period of eleven hours was selected for analysing error manoeuvres and other deviant behaviour for each approach direction.

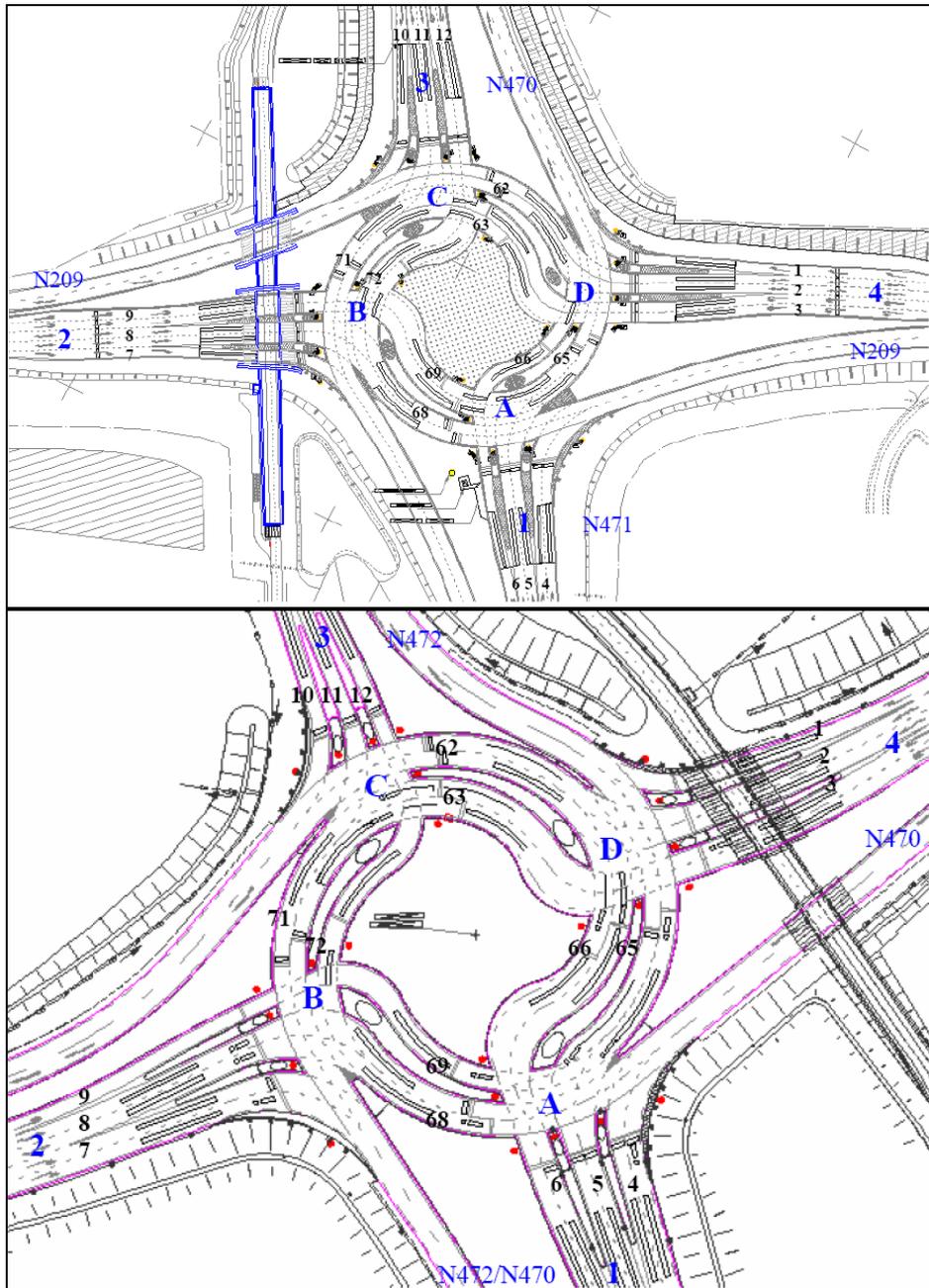
### **1.3 Road user surveys**

Whereas road scene analyses provide insight in an expert judgment of what a road user encounters when negotiating the turbo roundabout, the video-based analysis shows what road user behaviour is actually displayed at a signalised turbo roundabout. Then still the question arises how road users actually experience a signalised turbo roundabout. A questionnaire about the functioning of the Doenkadeplein is taken from in total 53 road users at a nearby gas station. Questions included clarity of aspects such as route signing, filtering, path choice and right-of-way situation, surveyability of the situation before and on the roundabout, and the subjectively experienced traffic safety.

## **2. Lay-out of the two signalised turbo roundabouts**

Figure 2 gives the lay-out of the Doenkadeplein (top) and of the Tolhekplein (bottom). The diameter of both roundabouts is about 110 m. On the roundabout itself, no exchange of traffic between directional lanes is foreseen (although possible by performing specific manoeuvres), traffic has to make their route choice before actually entering the roundabout. Most approach directions have two traffic lanes each, some have only one. For the greater part, physical elements separate the different directions.

Figure 2: Lay-out of the signalised turbo roundabout Doenkadeplein (intersection road N209 and N471) (top) and of the Tolheklein (intersection road N472 and N470) (bottom) with approach branches 1 through 4 and intersection areas A through D as used for the behavioural observations.



### 3. Road scene analysis

By means of a road scene analysis, an inventory was made for each approach direction of both turbo roundabouts of the information elements a road user encounters while approaching and negotiating the roundabout and how that may influence his behaviour and decision-making at a given place and a given time moment. For a detailed description of the analysis, the reader is referred to Horst et al. (2008). Here we will give the example of one approach, viz. approach 1 at the Doenkadeplein (see Figure 1, and 2 top, southern entry). This approach is rather complex due to a turbo roundabout (no traffic lights) just before the signalised turbo roundabout (within 200m) with already a view on the route signing of the second roundabout, see Figure 3. After passing the turbo roundabout, the approach of the

signalised turbo roundabout consists of one left-turn lane, two straight-on lanes, and two right-turn lanes, see Figure 4.

Figure 3: Turbo roundabout just before approaching the Doenkadplein from the south (approach 1 in Figure 2 top).



Figure 4: Southern approach branch of the Doenkadeplein, with a consistent coupling between route sign arrows and road surface arrows.



Because of the consistent coupling between the arrow indicators on the gantry panels and the directional roundabout arrows painted on the road surface, it is directly clear to the road user which lane one has to choose for which direction. But after this point, no other route information or confirmation of the choice made is presented while entering and negotiating the turbo roundabout itself. The lack of route information on the turbo roundabout itself or at the exit lanes may result in hesitating behaviour and perhaps undesired lane changes on the roundabout. For example, if a driver thinks he is in the wrong lane (he wants to turn left while he is on the straight-on lane), the space on the roundabout (see Figure 2 at D) allows him to do so, see Figure 5. Also the traffic sign with the two arrows suggests that it is allowed to pass at both sides of the separation island, but this may be an unexpected manoeuvre for the traffic from behind on the left-turn lane. Turning left seems to be the most complex task at turbo roundabouts, and may result in several undesired error manoeuvres. Especially, the path choice at the second left turn signal (with an arrow shape diagonally top left) before entering area D (see Figure 2), may be problematic. At this point, a road user may turn left immediately instead of following the lane he is in, and enter the

left-turn lane for the traffic from the right (and making in fact a U-turn with heading in the direction he is coming from). Once he discovers his mistake, then another switching of carriageways is needed to go in the intended direction in area C against the direction of the road surface yaw teeth marking.

Figure 5: Left-turn manoeuvre from straight-on lane in area D of the Doenkadeplein, see Figure 2 top.



#### 4. Video-based analysis of road user behaviour

Figure 6: Video recordings at Doenkadeplein with three video cameras; top left: approach direction from the south (direction 1 in Figure 2); bottom left: overview of central area; bottom right: close-up of furthest area (area C in Figure 2) of the roundabout at the opposite side of the cameras.



To register the actual behaviour of road users at the two signalised turbo roundabouts, digital video-recordings have been made by means of three video cameras unobtrusively mounted in existing public lamp posts at the southern approach. One camera was looking backwards to observe the area of the filtering lanes. Two cameras were looking northbound, one providing an overview of the central part of the roundabout and the third camera provided a close-up of the area furthest away from the cameras, see Figure 6. Video recordings have been made in the third week of October 2007. In total, three 24-hours recordings were available for each turbo roundabout. Out of these recordings, eleven hours have been selected (7:30- 18:30) for a detailed analysis of error manoeuvres and other deviant behaviour for each approach branch. In Horst et al. (2008) a distinction is made between peak hour periods and off-peak hours. During off-peak hours, error manoeuvres appear to occur 1.9 times as frequent as in peak hours when related to the total number of vehicles that passed (Horst, et al., 2008). Table 1 gives the number of error manoeuvres by approach direction and entering lanes. The category 'Other' mainly deals with running red, late filtering, or peculiar events which not have to do with the functioning of the turbo roundabout itself. The right-turn manoeuvre has been excluded from further analysis as this manoeuvre can be conducted without much interference with the functioning of the turbo roundabout as such.

Table 1: Number of error manoeuvres at the Doenkadeplein by approach direction (1-4, see Figure 2) and entering lanes (left-turn, straight-on); other = running red, late filtering, etc..

| <b>From Direction</b> | <b>Left-turn</b> | <b>Straight-on</b> | <b>Other</b> | <b>Subtotal</b> | <b>Percentage of total</b> |
|-----------------------|------------------|--------------------|--------------|-----------------|----------------------------|
| <i>1</i>              | 27               | 5                  | 12           | 44              | 25%                        |
| <i>2</i>              | 3                | 4                  | 1            | 8               | 5%                         |
| <i>3</i>              | 44               | 3                  | 2            | 49              | 28%                        |
| <i>4</i>              | 65               | 6                  | 1            | 72              | 42%                        |
| <b>Total</b>          | <b>139</b>       | <b>18</b>          | <b>16</b>    | <b>173</b>      | <b>100%</b>                |
| <b>%</b>              | <b>80.4%</b>     | <b>10.4%</b>       | <b>9.2%</b>  | <b>100%</b>     |                            |

Table 2: Number of error manoeuvres at the Doenkadeplein by approach direction and type of error (Left-turn inside-out: directly after 2nd light turning left, at next light going to the right again; complex: several times changing lanes resulting in a complete (or more) rounding of the roundabout; SO->LT: Coming from Straight-on lane turning left, LT->SO coming from left-turn lane going straight on by changing lanes once at the roundabout.

| <b>From direction</b> | <b>Left-turn inside-out</b> | <b>U-turn</b> | <b>Complex (complete around)</b> | <b>SO -&gt; LT or LT -&gt; SO</b> | <b>Filtering</b> | <b>Other</b> |
|-----------------------|-----------------------------|---------------|----------------------------------|-----------------------------------|------------------|--------------|
| <i>1</i>              | 19                          | 6             | 4                                | 2                                 | 3                | 9            |
| <i>2</i>              | 2                           | 1             | 3                                | 1                                 | -                | 1            |
| <i>3</i>              | 29                          | 10            | 6                                | 2                                 | 2                | 0            |
| <i>4</i>              | 30                          | 20            | 19                               | 2                                 | -                | 1            |
| <b>Total</b>          | <b>80</b>                   | <b>37</b>     | <b>32</b>                        | <b>8</b>                          | <b>5</b>         | <b>11</b>    |
| <b>%</b>              | <b>46.2</b>                 | <b>21.4</b>   | <b>18.5</b>                      | <b>4.6</b>                        | <b>2.9</b>       | <b>6.4</b>   |

The greater part of the error manoeuvres (80.4%) occurs by vehicles that enter the turbo roundabout from the left-turn lane(s). The proportion of error manoeuvres relative to the total number of passed vehicles during the period analysed, is 0.55%. That does not seem high, but 173 error manoeuvres for a time period of 11 hours is not marginal given the amount of traffic that makes use of the turbo roundabout. In an earlier study with long-term video observations at complex signalized intersections the error rates were much lower (Horst, et al., 2007). Approaching from direction 4 appears to result in the highest number of errors (42%), followed by direction 1 and 3 (25 en 28%, respectively). Traffic from direction 2 shows the lowest number of errors (5%). Table 2 makes a distinction in type of error manoeuvre. Two-third of the errors (left-turn inside-out + U-turn) consists of turning directly left at the 2<sup>nd</sup> left-turn light at the roundabout. For the complex manoeuvres one changes direction on the turbo roundabout several times, either indicating that one does not know where to go to, or that one is completely confused about the right path choice for a given manoeuvre. From the 32 error manoeuvres of this type, finally 18 drivers that arrive on the left-turn lane turn left, whereas 8 go straight on and 3 turn right, 4 return in the direction they came from, 4 that arrive for straight-on turn right.

Table 3: Number of error manoeuvres at the Tolhekplein by approach direction (1-4, see Figure 3) and entering lanes (left-turn, straight-on, other).

| <b>From Direction</b> | <b>Left-turn</b> | <b>Straight-on</b> | <b>Other</b> | <b>Subtotal</b> | <b>Percentage of total</b> |
|-----------------------|------------------|--------------------|--------------|-----------------|----------------------------|
| <i>1</i>              | 45               | 13                 | 11           | 69              | 45.1%                      |
| <i>2</i>              | 8                | 13                 | 4            | 26              | 17.0%                      |
| <i>3</i>              | 9                | 6                  | 16           | 31              | 20.3%                      |
| <i>4</i>              | 18               | 7                  | 2            | 27              | 17.6%                      |
| <b>Total</b>          | <b>80</b>        | <b>40</b>          | <b>33</b>    | <b>153</b>      | <b>100%</b>                |
| <b>%</b>              | <b>52.3%</b>     | <b>26.1%</b>       | <b>21.6%</b> | <b>100%</b>     |                            |

Table 3 gives the results of the error manoeuvres for the second turbo roundabout, the Tolhekplein by approach direction, and entering lanes. The category 'Other' mainly deals with running red, ghost riding (directly turning left when entering the turbo roundabout), late filtering, or peculiar events which not have to do with the functioning of the turbo roundabout itself. The proportion of error manoeuvres relative to the total number of passed vehicles during the period analysed, is 1.07%, twice as high as at the Doenkadeplein. When we compare the relative number of error manoeuvres during peak and off-peak hours, then off-peak hours result in 3.5 times as many errors than during peak hour periods. About half of the error manoeuvres (52.3%) occurs by vehicles that enter the turbo roundabout from the left-turn lane(s). Approaching from direction 1 appears to result in the highest number of errors (45.1%), whereas the other approach directions score about equally high (17-20%).

Table 4: Number of error manoeuvres at the Tolhekplein by approach direction and type of error (Left-turn inside-out: directly after 2<sup>nd</sup> light turning left, at next light going to the right again; complex: several times changing lanes resulting in a complete (or more) rounding of the roundabout; SO->LT: Coming from Straight-on lane turning left, LT->SO coming from left-turn lane going straight on by changing lanes once at the roundabout, SO-> RT coming from straight-on lane directly turning right at 1<sup>st</sup> light.

| From direction | Left-turn inside-out | U-turn      | Complex (complete around) | SO -> LT<br>or<br>LT -> SO<br>or<br>SO -> RT | Filtering   | Other       |
|----------------|----------------------|-------------|---------------------------|--|-------------|-------------|
| 1              | 26                   | 7           | 12                        | 15   | 4           | 6           |
| 2              | 5                    | 1           | 3                         | 13   | -           | 4           |
| 3              | 4                    | 4           | 2                         | 6  | 12          | 4           |
| 4              | 1                    | 15          | 1                         | 8  | -           | 2           |
| <b>Total</b>   | <b>36</b>            | <b>27</b>   | <b>18</b>                 | <b>42</b>                                    | <b>16</b>   | <b>16</b>   |
| <b>%</b>       | <b>23.2</b>          | <b>17.4</b> | <b>11.6</b>               | <b>27.2</b>                                  | <b>10.3</b> | <b>10.3</b> |

Table 4 makes a distinction in type of error manoeuvre. 40.6% of the errors (left-turn inside-out + U-turn) consists of turning directly left at the 2<sup>nd</sup> left-turn light at the roundabout. For the complex manoeuvres one changes direction on the turbo roundabout several times, either indicating that one does not know where to go, or that one is completely confused about the right path choice for a given manoeuvre. From the 18 error manoeuvres of this type, finally 6 drivers that arrive on the left-turn lane turn left, whereas 6 go straight and 2 turn right, 1 driver that arrives for straight-on finally goes straight on, 1 turns left and 2 turn right.

## 5. Road Users survey

A questionnaire, consisting of in total 12 questions about their experience with the turbo roundabout and 7 demographic questions, was taken by two interviewers at a nearby gas station. In total 53 interviews were completed, with 40 passenger car drivers and 13 truck drivers. Questions included aspects such as clarity of route signing, of filtering, of path to be taken, and of right-of-way situation; surveyability of the situation when approaching and negotiating the turbo roundabout; experienced traffic safety, conflicts with other road users, errors and mistakes. Typical figures for positive clarity and surveyability scores were around 60% for passenger car drivers, and around 80% for truck drivers. Usually, in comprehensibility studies a criterion value of 80-85% is used as norm (e.g. Martens & de Ridder, 2002), and based on this, the scores for passenger car drivers do not comply. From the survey results it can be concluded that the interviewed road users are reasonably positive about the signalised turbo roundabout, but they indicate that habituation is very important. A lot of road users admitted to have made several mistakes (wrong traffic lane choice) when the situation was new. Many respondents also indicate that they frequently see other road users make similar mistakes. For more details of the responses, the reader is referred to Horst, et al. (2008).

## 6. Discussion and conclusions

Fortuijn (2003) indicates that one of the design principles for a signalised multi-lane turbo roundabout is that it fulfils the requirement for a normal roundabout, i.e. that the roads connect radially to the roundabout (that reduces the approach and entering speeds) and that traffic on the roundabout have the right-of-way. Moreover, at a signalised turbo roundabout there are buffer zones for left-turning or straight-on traffic on the roundabout that enables a

two-phase traffic control scheme, and consequently in a reduction of waiting times and an increase in traffic capacity. However, the lay-out of a turbo roundabout requires that road users make their route choice and resulting lane choice before entering the turbo roundabout. Once they are on the roundabout they have to follow the carriageway they are on. In practice, some people behave differently and start changing lanes on the turbo roundabout. The road scene analyses indicate that, in general, at both turbo roundabouts, maximum effort is devoted by the designer to carefully indicating possible directions before entering the roundabout. The route signing is uniformly and consistently designed with the same destinations on the pre-direction sign panels and on one main gantry sign panel, and roundabout arrows as painted on the road surface uniformly indicated on the gantry panel just in front of the turbo roundabout. Once one has passed the gantry sign, however, no further route directions are presented, neither on negotiating or leaving the roundabout. This may result in hesitating and/or uncertain behaviour. The video-based behavioural analyses reveal that filtering during the approach of the turbo roundabouts is conducted rather smoothly. In line with the outcome of the road scene analyses, on both roundabouts the left-turn manoeuvre appears the most problematic one. Turning left directly beyond the first traffic light is to be considered the most serious error because one enters the roundabout against the driving direction (ghost riding). This error only occurred at the Tolhekplein, in total six times. With respect to the path choice driving on the roundabout, the situation for left-turning traffic at the second traffic signal (with an arrow shape diagonally top left) stands out most prominently. At this point, a lot of road users turn left right away instead of going straight on in their lane, and enter the left-turn carriageway for the traffic from the right. A great part of them discover that they are on the wrong carriageway and switch back to the right adjacent carriageway at the next traffic signal (against the direction of the road surface yaw tooth marking). Complex error manoeuvres (several times a carriageway switching on the roundabout resulting in at least one complete round) occur at both roundabouts (Doenkadeplein 18.5%, Tolhekplein 11.6%). It is clear that one does not know where to go to or that one loses the right path choice. From the survey results it can be concluded that the interviewed road users are reasonably positive about the signalised turbo roundabout, but they indicate that habituation is very important. A lot of road users admitted that when the situation was new, they made several mistakes (wrong traffic lane choice). Many respondents also indicate that they frequently see other road users make similar mistakes.

On the one hand, approaching and negotiating signalised turbo roundabouts appear to be a complicated manoeuvre, especially for the less familiar road user. From the survey it appears that once one has learned how to behave, one appreciates this intersection solution because of a better throughput and lower delay times. But for the less familiar road user this type of intersection remains problematic and results in several types of error manoeuvres, of which some rather serious (wrong way) or resulting in uncertain and unsafe behaviour. We expect that recommendations for improving the lay-out and outfit of a signalised turbo roundabout (see Horst et al, 2008) will reduce the number of error manoeuvres, but not fully exclude them. On the other hand, the traffic throughput analysis reveals a much higher capacity of a signalised turbo roundabout than of a conventional signalised intersection, but at a cost of a higher number of red runners. Based upon the results of the behavioural study and the road user survey, we recommend to be careful in applying this type of intersection, and only consider application if the traffic capacity for heavy crossing flows really requires so.

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