Rapport nº 2020-R-03-FR

Sécurité des cyclistes dans les ronds-points à trafic mixte

Analyses vidéo des indicateurs de comportement et de conflit

Service public fédéral
Mobilité et Transports

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Auteurs : Giulia Pulvirenti, Tim De Ceunynck, Stijn Daniels

Éditeur responsable : Karin Genoe
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Résumé

La littérature scientifique montre que la transformation des carrefours en ronds-points entraîne une baisse du nombre d'accidents corporels parmi les occupants des véhicules à moteur et les piétons, mais l'effet sur la sécurité des cyclistes est plus incertain, voire négatif. Cette étude a recours à des analyses vidéo semi-automatisées pour étudier la sécurité et le comportement des cyclistes dans les ronds-points à trafic mixte (c'est-à-dire les ronds-points sans aménagements pour les cyclistes). Ce résumé décrit brièvement la conception de la recherche et les principales conclusions de l'étude. Pour plus de détails, nous renvoyons le lecteur intéressé au document complet (en anglais) qui est annexé au présent rapport. Cet article a récemment été soumis pour publication dans une revue scientifique.

Quatre ronds-points ont été observés, dont deux avec un diamètre plus petit (+/-20m) et deux avec un diamètre plus grand (+/-30m). Trois ronds-points étaient situés en agglomération, un rond-point juste en périphérie de l'agglomération avec une limitation de vitesse fixée à 50 km/h. Le comportement et les interactions entre les cyclistes et les autres usagers de la route ont été analysés à l'aide de sept indicateurs : la vitesse, la position latérale et cinq indicateurs utilisés pour décrire la proximité des usagers de la route dans le temps et/ou l'espace (Time-to-Collision minimal (TTCmin), Post Encroachment Time (PET), T2, min, la distance latérale de dépassement et la distance minimale de suivi). En outre, des informations ont été recueillies sur la position latérale et la vitesse des cyclistes qui n'interagissent pas avec les autres usagers de la route ; nous appelons ce dernier groupe cyclistes circulant librement (sans interaction - free-flow). La position latérale et la vitesse des cyclistes en interaction avec les autres usagers de la route ont été comparées à celles des cyclistes circulant librement. Pour chaque rond-point, on a réalisé une analyse basée sur 16 h d'images de tous les cyclistes circulant librement, de toutes les interactions entre un cycliste et un autre usager de la route, et de toutes les interactions étroites (c'est-à-dire les interactions avec peu de marge dans le temps et/ou l'espace entre les deux usagers de la route en interaction). Ensuite, les interactions étroites obtenues sur la base des 16h d'images ont été sélectionnées pour une analyse plus approfondie parce que les interactions étroites sont significativement moins fréquentes que les interactions ordinaires et les cyclistes circulant librement.

Les analyses comportementales montrent que les deux types de cyclistes (circulant librement et en interaction avec un autre usager de la route) roulent plus vite dans les ronds-points de plus grand diamètre que dans les ronds-points de plus petit diamètre. Les cyclistes roulent également plus près de l'îlot central dans les ronds-points de plus grand diamètre que dans les ronds-points de plus petit diamètre. Les cyclistes suivis par une voiture ont tendance à se rapprocher de l'extérieur de la route sur les deux types de ronds-points.

L'analyse des « indicateurs de quasi-accidents » (TTCmin, PET, T2 min) révèle que les interactions étroites dans les ronds-points de plus grande et de plus petite taille surviennent régulièrement. Le pourcentage d'interactions désignées comme étroites par l'un des ceurs était très similaire, à savoir environ 8% des interactions observées, tant sur les plus grands que sur les plus petits ronds-points. Le type d'interaction le plus courant était la situation où un cycliste entre dans un rond-point.

L'analyse de la distance latérale de dépassement a révélé que les cyclistes qui dépassent une voiture laissent moins de distance latérale que les voitures qui dépassent les cyclistes. En ce qui concerne la distance latérale de dépassement, aucune différence n'a été constatée entre les ronds-points de plus grand diamètre et ceux de plus petit diamètre. L'analyse de la distance minimale de suivi a montré que les cyclistes qui se trouvent derrière une voiture laissent moins de distance que les voitures qui se trouvent derrière un cycliste.

L'étude a mis en avant les vastes possibilités d'utilisation des techniques d'analyses vidéo semi-automatisées pour analyser le comportement et les interactions dans la circulation, et mesurer objectivement la gravité des interactions. L'étude a fourni des informations détaillées sur le comportement, les interactions avec les autres usagers de la route et les interactions étroites avec les cyclistes dans les ronds-points à trafic mixte. Bien que des différences de comportement aient été constatées entre les ronds-points de grand diamètre et ceux de plus petit diamètre, cette étude ne permet pas de conclure s'il existe des différences de sécurité entre des ronds-points de diamètre différent.

Annexe: document complet

Abstract

Although converting an intersection into a roundabout has been shown to result in fewer injury accidents for both motor vehicle drivers and pedestrians, the effect on bicyclists' safety is unclear or even negative. This study focuses on roundabouts without bicycle facilities (i.e., mixed traffic conditions) and makes use of semi-automated video observation software with the aim of analysing bicyclists' behaviour and safety on roundabouts with different diameter. Four urban roundabouts in Belgium are observed. Interactions between bicyclists and other vehicles are analysed using speed, lateral position and five indicators to describe the closeness of interactions (TTC_{min}, PET, $T_{2\ min}$, lateral overtaking proximity and minimum distance headway). Additionally, the lateral position and riding speed of bicyclists that are in interaction with other vehicles is compared with the behaviour of bicyclists that are not in interaction with other vehicles.

The behavioural analysis revealed that regardless of the type of condition (free-flow bicyclists or different interactions bicyclist-car), bicyclists always ride faster on roundabouts with big diameter and slower on roundabouts with small diameter. Moreover, bicyclists ride closer to the central island on roundabouts with big diameter compared to roundabouts with small diameter for all the conditions analysed.

The analysis of surrogate safety indicators (TTC_{min}, PET, $T_{2\ min}$) revealed that close interactions between bicyclists and cars are relatively frequent at both small and big roundabouts. The percentages of close interactions are more or less equal for roundabouts with big diameter (7.86% of observed interactions) and roundabouts with small diameter (8.24%). The analysis of the indicators to describe the closeness of interactions also showed that the closest interactions at roundabouts are all situations where the bicyclist has a leading role. The analysis of the most common types of close interactions revealed indeed that the most common close interactions are interactions where the bicyclist is entering the roundabout. The analysis of lateral overtaking proximity showed that bicyclists who overtake a car take smaller lateral overtaking proximities compared to cars overtaking a bicyclist. The analysis of minimum distance headway finally revealed that bicyclists who ride behind a car take smaller distance headways compared to cars driving behind a bicyclist.

Keywords

Road safety; Bicycle-vehicle interactions; Road user behaviour; Roundabouts; Surrogate safety indicators; Video analysis.

1. Introduction

Active modes of transportation such as cycling are promoted as a way to provide health benefits, mitigate traffic congestion and reduce air pollution (Götschi et al., 2016). Transport authorities and policy makers continue to encourage people to use sustainable travel modes due to the benefits they offer society in terms of health, reduced congestion, and associated environmental impacts. However, safety and security are among the main barriers associated with the use of sustainable travel modes in general, and walking and cycling in particular (Akgün et al., 2018; De Ceunynck et al., 2019). The promotion of cycling brings health benefits for citizens of all age groups and to further favour the use of bicycles, special attention should be dedicated to cycling safety. Infrastructure design plays a major role in creating a safer travel environment for road users.

Although converting an intersection into a roundabout has been shown to result in fewer injury accidents for both motor vehicle drivers and pedestrians (Canale et al., 2015; Elvik and Vaa, 2009; Hydén and Várhelyi, 2000; NCHRP, 2007; Retting et al., 2001), the effect on bicyclists' safety is unclear or even negative (Daniels et al., 2008). A lot of studies have already focused on bicyclists' safety at roundabouts (Akgün et al., 2018; Hollenstein et al., 2019; Jensen, 2017) but little is known about the interactions between bicyclists and other road vehicles at roundabouts. Better understanding of how bicyclists move and interact with other vehicles at roundabouts is essential for improving bicyclists' safety.

This study focuses on roundabouts without bicycle facilities (i.e., mixed traffic conditions) and makes use of semi-automated video observation software with the aim of analysing bicyclists' behaviour and safety on roundabouts with different diameter. Interactions between bicyclists and other vehicles are analysed using speed, lateral position and several surrogate safety indicators, and the behaviour of bicyclists that are in interaction with other vehicles is compared with the behaviour of bicyclists that are not in interaction with other vehicles.

2. Background

International studies have unanimously demonstrated that the construction of roundabouts is an effective measure to improve road traffic safety. Various studies have examined the public opinion on roundabouts and demonstrated that road users are generally favourable to roundabouts (Distefano et al., 2019, 2018; Leonardi et al., 2019; Retting et al., 2002). In general, roundabouts reduce the number of injury accidents. Over the last decades several studies have been carried out on the effects of roundabouts on traffic safety. A lot of studies reported a considerable decrease in the number of accidents in roundabouts compared to standard intersections (De Brabander et al., 2005; Elvik, 2003; Persaud et al., 2001). Less is known about the safety effects of roundabouts for particular types of road users, such as bicyclists (Daniels and Wets, 2005). A Belgian study found that roundabouts increase the number of bicyclist injury accidents by 27% and fatal bicycle accidents by 41-46% (Daniels et al., 2008). Earlier research showed that signalized junctions were performing better than roundabouts for bicyclists (De Brabander and Vereeck, 2007). However, Jensen, 2017 stated that in high speed limit locations, converting intersections to single lane roundabouts decreases the number of crashes and casualty severity of bicyclists.

Bicycle safety is influenced by roundabout design. Daniels et al. (2011, 2009) found that roundabouts with marked cycle lanes adjacent to the circulation are less safe for bicyclists than roundabouts without bicycle facilities, and roundabouts with separate cycle paths are in turn safer than roundabouts with no bicycle facilities. Jensen (2017) conducted a comprehensive study on the impact of single lane roundabouts with different sizes of central islands on bicyclist safety and found that single lane roundabouts with a 20–40 m central island were safer than those having a larger or smaller central island radius. Reid and Adams (2011) highlighted that all road infrastructure related factors, such as the number of flare lanes on approach, half width on approach, entry path radius, number of arms, central radius, entry width, number of lanes on approach and type of roundabout are fundamental factors in the decision-making process of how to reduce bicyclist casualties. Hels and Orozova-Bekkevold (2007) assessed the impact of geometric design features on bicyclist accident occurrence by evaluating 'drive curve' (i.e. the entry path radius). They concluded that a higher drive curve (entry path radius) increases the probability of bicyclist accident*.* Daniels et al. (2010) stated that increase of age of bicyclist results in an increase in casualty severity at roundabouts for all types of road users; however, the impact of gender is uncertain. In addition, they found that the severity of casualties at roundabouts increased at night and outside of built up areas regardless of the type of road users involved. Akgün et al. (2018) investigated which design factors influence bicyclist casualty severity at give way (non-signalized) roundabouts with mixed traffic and found that the probability of a serious casualty increases by approximately five times for each additional lane on approach and by 4% with a higher entry path radius.

The interaction between motorized and non-motorized road users has been an issue of contention for many years. Indeed, bicyclists and drivers differ significantly from each other in terms of speed, size, weight, and vulnerability, so that interacting with one or the other implies adapting our perceptions and our behaviour to these differences. Bicyclists' presence on the road may be considered annoying and a source of irritation by drivers (Basford et al., 2002). On the other hand, bicyclists complain that driver behaviour ranges from dangerous to illegal (Chapman and Noyce, 2013). The interaction between bicyclists and motorists is of particular interest because severe injuries and deaths often occur in collisions between a bicyclist and a motorized vehicle (Bíl et al., 2010; Chaurand and Delhomme, 2013; Matsui and Oikawa, 2015). The riskiest situation for bicyclists is interacting with a motorized vehicle (Bíl et al., 2010; Kim et al., 2007; Räsänen and Summala, 1998), particularly at an intersection (Carter et al., 2007; Reynolds et al., 2009; Wang and Nihan, 2004). For example, Kim et al., 2007 showed that more than 50% of crashes involving a bike and another vehicle (a car in 70% of the cases) occurred at an intersection.

Research on bicycle-overtaking manoeuvres has used the minimum lateral clearance between the bicyclist and the vehicle while the vehicle is passing as a surrogate measure for safety (Chapman and Noyce, 2013; De Ceunynck et al., 2017; Love et al., 2012; Walker et al., 2014). Previous research showed how lateral clearance is influenced by infrastructure design (e.g. presence of bike lanes) (Chapman and Noyce, 2013; Frings et al., 2014), the behaviour of the bicyclist (e.g. speed, steering angle, speed variation control) (Chuang et al., 2013), and the bicyclist's appearance (such as outfit, gender and helmet wearing) (Chuang et al., 2013; Walker, 2007; Walker et al., 2014). When motorists pass bicyclists, an event that happens frequently, close distances (lateral overtaking distances as well as following distances) are negatively perceived by bicyclists and may compromise their safety (De Ceunynck et al., 2017). A survey in Australia found that nearly 70% of 1830 bicyclists reported that the most common form of drivers' harassment was driving too close (Heesch et al., 2011).

3. Research questions

In order to explore the behaviour and the safety of bicyclists on roundabouts without bicycle facilities, the following research questions will be investigated in this study:

1. Does bicyclists' behaviour vary on roundabouts without bicycle facilities with regard to the diameter of the roundabout?
2. How does the presence of a vehicle affect the bicyclists' behaviour when riding on a roundabout without bicycle facilities?

3. How frequently are bicyclists involved in close interactions with cars?
4. What types of close interactions are most common, and how do the patterns differ between roundabouts with a different diameter?

4. Methodology

4.1 *Study locations*

Four urban roundabouts without bicycle facilities in the region of Brussels (Belgium) were observed. Since one of the aims of the study was to analyse the influence of the diameter of roundabouts on bicyclist behaviour, the four roundabouts were chosen in order to be similar from a geometric and design point of view except for the diameter. The roundabouts selected have therefore four legs that intersect at perpendicular angle, absent or low longitudinal slope and truck apron. As for the diameter, two roundabouts have a diameter of 30 meters approximately and two roundabouts have a diameter of 20 meters approximately. Roundabouts 2-4 are located in built-up area with a speed limit of 50 km/h; roundabout 1 is located at the border of the built-up area but with a speed limit of 50 km/h as well.

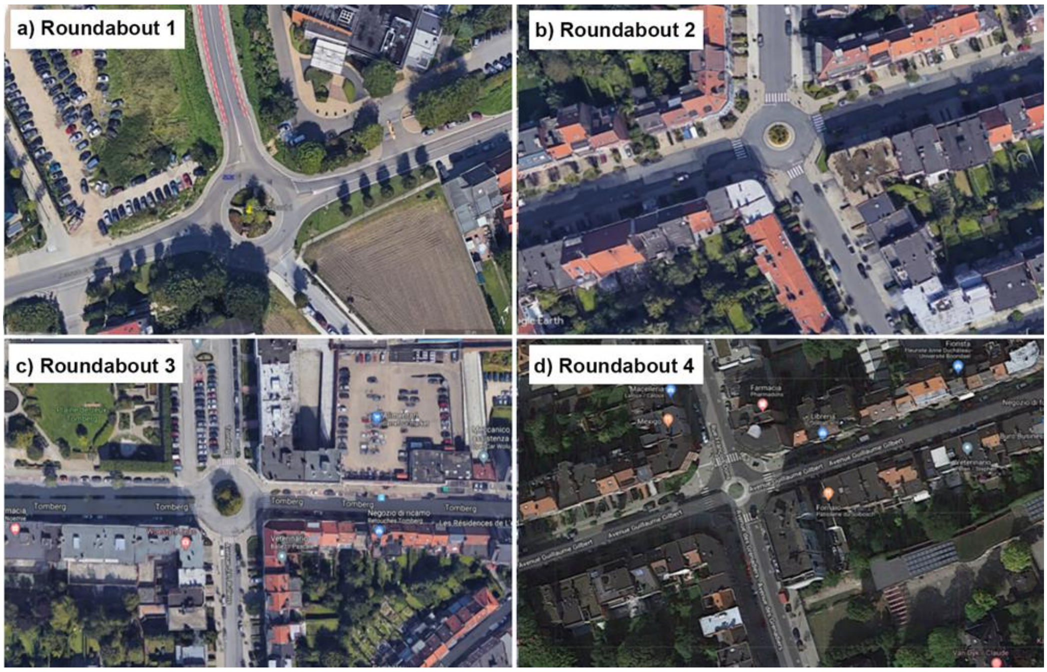


Figure 1 – Observation sites: a) Roundabout 1 (Zaventem – D=32 meters); b) Roundabout 2 (Woluwe-Saint-Lambert – D=22 meters); c) Roundabout 3 (Woluwe-Saint-Lambert– D=30 meters); d) Roundabout 4 (Ixelles – D=20 meters).

The first roundabout (Fig. 1 a) is located in the municipality of Zaventem. It is located just outside the built-up area, in a zone with a speed limit of 50 km/h. It has a diameter of 32 meters. The second roundabout (Fig. 1 b) is located in the municipality of Woluwe-Saint-Lambert and has a diameter of 22 meters. The third roundabout (Fig. 1 c) is located in the municipality of Woluwe-Saint-Lambert and has a diameter of 30 meters. The fourth roundabout (Fig. 1 d) is located in the municipality of Ixelles and has a diameter of 20 meters.

More details about the four roundabouts are presented in Table 1. Roundabout 1, 2 and 3 have a full raised truck apron. Roundabout 4 has instead an at-grade textured truck apron, i.e. there is no difference in height between roadway and apron and there only is a difference in material. Because of this truck apron was considered part of the circulatory roadway width for roundabout 4.

Table 1 – Characteristics of the four roundabouts analysed.

Characteristic	Roundabout 1	Roundabout 2	Roundabout 3	Roundabout 4
Number of legs	4	4	4	4
Diameter [m]	32.00	22.00	30.00	20.00
Circulatory roadway width [m]	6.00	6.10	7.40	6.20

Truck apron width [m]	2.21	1.89	2.06	2.13

4.2 *Video data collection and analysis*

At each site, two video cameras were mounted on different light poles to record oncoming bicyclists and vehicles on the roundabout. Five days of video were recorded in February, March and April 2019 from 7:00 a.m. to 7:00 p.m. for each roundabout (60 hours per roundabout).

The video footage is processed using T-Analyst, a semi-automated video analysis software developed at Lund University. The software is calibrated to transform the image coordinates of each individual pixel to road plane coordinates, which allows the accurate determination of the position of an object in the image and the calculation of its trajectory. This allows the calculation of road users' speeds and positions, distances and traffic conflict indicators in an accurate and objective way (Polders et al., 2015).

Some of the collected indicators (such as lateral position) require a high level of accuracy in the measurements (De Ceunynck et al., 2017). To ensure a sufficiently high accuracy, each video camera was used to record oncoming vehicles and bicyclists on a single quadrant. The video data analysis regards therefore two consecutive quadrants of each roundabout, i.e. half of each roundabout (Fig. 2).

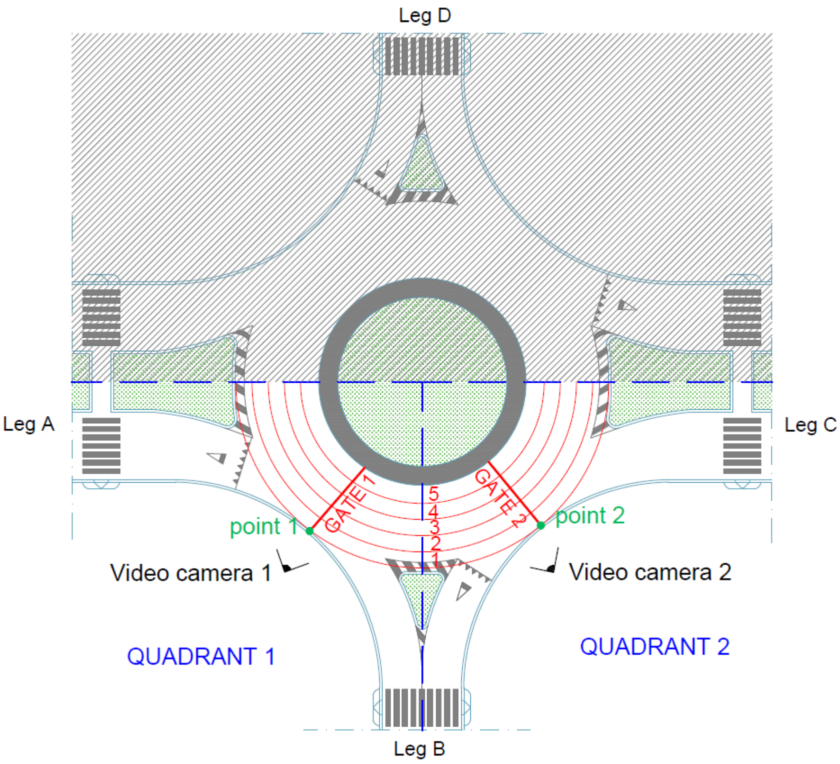


Figure 2 – Schematic representation of quadrants, video cameras position and gates.

All free-flow bicyclists and interactions between bicyclists and other vehicles that take place on the half roundabout during the observation period are selected for detailed analysis. Interactions between bicyclists and vehicles different from person cars (i.e. buses, trucks, motorcycles, bicyclists) are really few in number. The analysis developed in this paper regards therefore only free-flow bicyclists and interactions between bicyclists and person cars, in the remainder of this paper called "cars".

An interaction is defined as a situation in which two road users approach each other with such closeness in time and space that the presence of one road user can have an influence on the behaviour of the other (De Ceunynck et al., 2013). Four types of interactions are considered in order to take into account all the possible interactions between bicyclists and cars:

1- following interactions;

2- overtaking interactions;

3- entering interactions - the road user on the entry leg goes first;

4- entering interactions - the road user on the entry leg doesn't go first;

Following interactions are operationalised as each situation where a vehicle approaches a bicyclist or a bicyclist approaches a vehicle on the circulatory roadway to a distance of less than x meters, which equals the distance covered by the following vehicle or the following bicyclist in y seconds at a speed of z km/h. These situations can either be following situations where a vehicle is driving behind a bicyclist (named *following interaction – vehicle*) or following situations where a bicyclist is riding behind a road vehicle (named *following interaction – bicyclist*).
The speeds z, the temporal distances y and the resulting spatial distances x are equal to:

- **x=21 meters** for the roundabouts with big diameter (i.e. roundabout 1 and roundabout 3);
- **x=14 meters** for the roundabouts with small diameter (i.e. roundabout 2 and roundabout 4).

These values were deduced by the examination of a sample of following situations selected from the video observations of the four roundabouts analysed. First of all, the mean speeds in the middle of the quadrant of the following road users were calculated both for situations where a vehicle follows a bicyclist and for situations where a bicyclist follows a vehicle. Since the mean speed of bicyclists following vehicles was very similar to the mean speed of vehicles following bicyclists, it was considered the same mean speed both for bicyclists following vehicles and for vehicles following bicyclists (i.e. z=5.40 m/s=19.45 km/h for roundabouts with big diameter and z=4.63 m/s=16.7 km/h for roundabouts with small diameter). In order to identify the threshold temporal intervals y between interaction and no interaction situation, the speed variation $\Delta s=speed_0-speed_1$ of the following user related to the temporal interval t_0-t_1 was calculated for each situation. t_0 is the instant where the following road user is at the *minimum distance headway* from the preceding user and t_1 is the instant where the following user reaches the point 0 where the preceding road user was at the instant t_0. Each situation where this speed variation Δs was a reduction larger than 10% was considered as a following interaction because it can be assumed that the speed reduction of the following user is due to the presence of the preceding user. Other situations were considered as free-flow situations. The means of the temporal intervals for which the speed reductions were larger than 10% are y = 3.8 s for the roundabouts with big diameter and y = 3.0 s for the roundabouts with small diameter. The resulting distances x (obtained by multiplying the temporal intervals y and the speed z) are x=20,53 meters for the roundabouts with big diameter and x=13.89 meters for the roundabouts with small diameter, which are rounded respectively to x=21 meters and x=14 meters.

Overtaking interactions are operationalised as each situation where a vehicle overtakes a bicyclist or a bicyclist overtakes a vehicle on the circulatory roadway (named respectively *overtaking interaction – vehicle* and *overtaking interaction – bicyclist*).

Entering interactions – the road user on the entry leg goes first are operationalised as each situation where a road user (bicyclist or vehicle) enters the roundabout before another road user (vehicle or bicyclist) arriving from the quadrant on the left of the entry leg (named respectively *entering interactions – bicyclist enters first* and *entering interactions – vehicle enters first)*. These situations are considered interactions only when the road user on the entry leg can clearly see the other road user arriving on the circulatory roadway. This can be approximated to the situations where the road user is already on the quadrant on the left of the entry leg when the other road user is on the entry leg.

Entering interactions – the road user on the entry leg doesn't go first are operationalised as each situation where a road user (bicyclist or vehicle) enters the roundabout after another road user (vehicle or bicyclist) arriving from the quadrant on the left of the entry leg (named respectively *entering interactions – bicyclist doesn't enter first* and *entering interactions – vehicle doesn't enter first)*.

Free-flow bicyclists are defined as bicyclists who are not interacting with other vehicles. We consider therefore free flow bicyclists both bicyclists who ride the roundabout while no vehicles or other road users are on the whole roundabout and bicyclists who ride the roundabout when there are other road users on legs or parts of the roundabout which don't affect the trajectory of the free-flow bicyclist.

16 hours of video were analysed for each roundabout to identify free-flow bicyclists, interactions and close interactions (Video Analysis 1). 16 additional hours of video were then analysed for each roundabout to identify additional close interactions (Video Analysis 2). In order to identify close interactions, all situations that had a relatively high subjective level of unsafety were preselected from the additional 16 hours of video, with enough safety margin to ascertain that none of the truly severe situations were missed. Free-flow bicyclists and regular (non-close) interactions were not included in Video Analysis 2.

4.3 *Collected variables about behaviour*

For all events (both interactions and free-flow bicyclists), the following data related to bicyclists' behaviour are registered:

- Lateral position of the bicyclists in the middle of the quadrant, i.e. in the gates showed in Figure 2; for each roundabout 5 zones are considered for lateral position, as shown in Figure 2. The five lateral positions are obtained by dividing the circulatory roadway width in 5 equal parts.
- Normalized distance (N_d) from the edge of the circulatory roadway in the middle of the quadrant, i.e. in the gates showed in Figure 2; normalized distance is obtained by dividing the distance between the external edge of the circulatory roadway (point 1and point 2 in Figure 2 respectively for gate 1 and gate 2) and the centroid of the bounding box around the bicyclist (which approximately corresponds with the contact point of the tyres on the road) by the circulatory roadway width. For each gate, normalized distance takes therefore values between 0 (at the external edge of the circulatory roadway) and 1 (at the internal edge of the circulatory roadway). There is a direct correspondence between the five zones and the values of normalized distance: $0<N_d\leq0.2$ corresponds to zone 1; $0.2<N_d\leq0.4$ corresponds to zone 2; $0.4<N_d\leq0.6$ corresponds to zone 3; $0.6<N_d\leq0.8$ corresponds to zone 4; $0.8<N_d<1$ corresponds to zone 5.
- Riding speed of the bicyclist in the middle of the quadrant, i.e. in the gates showed in Figure 2. The riding speed is expressed in km/h.

For overtaking interactions, *lateral overtaking proximity* is additionally registered. For following interactions, *minimum distance headway* is additionally registered. *Minimum distance headway* and *lateral overtaking proximity* are expressed in meters.

4.4 *Indicators to describe closeness of interactions*

In order to evaluate the closeness of interactions, five indicators were chosen. The *Minimum Time-to-Collision* (TTC_{min}), the *Post-Encroachment-Time* (PET) and the *Minimum T2-value (*$T_{2\ min}$*)* are the surrogate safety indicators used to evaluate the closeness of the interactions. In addition to these, the *lateral overtaking proximity* of overtaking interactions, and the *minimum distance headway* of following interactions are analysed.

Time to collision (TTC) is an indicator that calculates the time remaining before the collision if the involved road users continue with their respective speeds and trajectories (Hayward, 1972). TTC_{min} is the most commonly used surrogate safety indicator to identify serious conflicts (Laureshyn et al., 2016). Research suggests that TTC_{min} values lower than 1.5 s are rarely observed in normal interactions and can therefore be considered close interactions (Brown Gerald R., 1994; Van Der Horst A. R. A., 1990). A necessary precondition for the TTC is that two road users are on a collision course; in case there is no collision course, no TTC-values can be calculated.

Post-Encroachment-Time (PET) describes the temporal difference between the two road users occupying the same point in space. These concepts are intrinsically different in nature: as previously described, the TTC depends on predicting what would happen if the road users travel unaware of each other and has a finite value only when the road users are predicted to be on a collision course, while the PET observes the outcome of a crossing course (Laureshyn et al., 2010). All PET values lower than 1.0 seconds were considered close interactions based on scientific literature (Ismail et al., 2009; Peesapati et al., 2013).

The *T2-value* is the predicted arrival time of the second road user, calculated while the first road user has not left the conflict point yet. When the road users are on a collision course, T_2 is equal to TTC (Laureshyn et al., 2010). During a collision course predicted at constant speed and direction, this value equals the TTC, since it is the second vehicle arriving at the common spatial zone that would initiate the collision. The T2-value is therefore able to deal with the transfer between a collision course and crossing course. Literature is not conclusive on the most valid threshold value of $T_{2\ min}$, since it is a fairly new and not yet frequently applied indicator. However, the indicator extends the concept of TTC_{min}. The $T_{2\ min}$ value tends to reach a lower value than TTC_{min} for most interactions for which there is a collision course for part of the duration of the interaction. Consequently, a lower threshold value should be applied to distinguish close interactions from normal interactions than for the TTC_{min} indicator. Therefore, a threshold value of 1s is adopted for the $T_{2\ min}$ indicator.

The literature review has shown that the *lateral overtaking proximity* is an important aspect of bicyclists' safety. Research suggests that accidents where bicyclists are struck by an overtaking motorist are disproportionately dangerous to the bicyclists, because in such accidents motor vehicles usually drive much faster than, for instance, in accidents with turning vehicles (Pai, 2011; Stone and Broughton, 2003; Walker et al., 2014). The Belgian Traffic Code imposes a minimum lateral distance of 1 m when overtaking a bicyclist inside built-up areas and a minimum lateral distance of 1.5 m when overtaking a bicyclist outside built-up areas. However, the requirement of keeping a lateral distance of 1.5m outside built-up areas was only implemented on May 31st 2019; before that date, the required lateral distance was 1m as well. All recordings date before this change in the traffic code, which means that a minimum lateral overtaking of 1m applied at all roundabouts at the time of the study. Therefore, overtaking manoeuvres with a *lateral overtaking proximity* of less than 1 m are in this study considered to be close interactions in line with previous work by De Ceunynck et al. (2017).

Minimum distance headway (the distance between the rear of the leading vehicle and the front of the following vehicle, expressed in meters) is highly defining for the risk of rear-end collisions (Evans and Wasielewski, 1982). Close-following is generally considered risky (Rajalin et al., 1997). Close-following, is risky because, other things being equal, short following distances provide less time to react to a lead car's braking or major disturbances ahead.. In this study the patterns of *minimum distance headway* for following interactions are therefore analysed. It is difficult to identify a clear threshold between what is a 'close following interaction' versus a 'not close following interaction' based on the *minimum distance headway*, because the same *minimum distance headway* could be more or less dangerous if the speed is different. Anyway, it can still be considered that closer following is more dangerous.

5. Results and discussion

5.1 Analysis of free-flow bicyclists and bicyclists-vehicle interactions

The database obtained from the analysis of 16 hours of video for each roundabout (Video Analysis 1) consists of 974 records in total, 544 of which are bicycle-vehicle interactions and 430 are free-flow bicyclists. Table 2 shows the number of observed situations for roundabouts with big diameter (i.e. roundabouts 1 and 3) and for roundabouts with small diameter (i.e. roundabouts 2 and 4). The following sections will analyse behavioural aspects of free-flow bicyclists and bicyclist-vehicle interactions such as speed, lateral position and occurrence of close interactions.

Table 2 – Number of observed situations for roundabouts with big diameter (roundabouts 1 and 3) and roundabouts with small diameter (roundabouts 2 and 4).

Condition	Big diameter	Small diameter	Total	
			Count	Percent
1. Free-flow bicyclists (no interaction)	188	242	430	44.15
2. Following interactions - vehicle	80	84	164	16.84
3. Following interactions - bicyclist	53	45	98	10.06
4. Overtaking interactions - vehicle	10	2	12	1.23
5. Overtaking interactions - bicyclist	5	3	8	0.82
6. Entering interactions - vehicle enters first	11	13	24	2.46
7. Entering interactions - bicyclist enters first	33	23	56	5.75
8. Entering interactions - vehicle doesn't enter first	50	41	91	9.34
9. Entering interactions - bicyclist doesn't enter first	44	47	91	9.34
Total interactions	286	258	544	55.85
Total	474	500	974	100.00

5.1.1 Behavioural aspects of free-flow bicyclists

To answer the question of whether free-flow bicyclists' behaviour vary on roundabouts without bicycle facilities with regard to the diameter of the roundabout, two univariate analyses of variance (ANOVA) were conducted considering only free-flow bicyclists. The sample considered for these analyses is therefore 430 free-flow bicyclists. The dependent variables are the bicyclists' riding speed for the first ANOVA and the lateral position in the middle of the quadrant for the second one. Riding speed in the middle of the quadrant is expressed in km/h and is subdivided in four ranges (i.e. *≤15 km/h*, *15-20 km/h*, *20-25 km/h*, *>25 km/h*). Lateral position in the middle of the quadrant is expressed as normalized distance from the edge of the circulatory roadway, so it can range from 0 to 1. The independent variable is for both ANOVAs the diameter of the roundabout (*big diameter* or *small diameter*). For all analyses the p-value was set at 0.05 to determine statistical significance. Table 3 shows the mean values of free-flow bicyclists' speed and lateral position. Table 4 shows the results of the ANOVA tests for free-flow bicyclists' speed and lateral position.

The ANOVA test for speed (Table 4) shows that speed is significantly different between the two different diameters ($p=0.000<0.05$). Looking at the mean values of speed (Table 3) it can be seen that free-flow bicyclists ride significantly faster on roundabouts with big diameter ($s_{mean}=21.16$ km/h) compared to roundabouts with small diameter ($s_{mean}=17.55$ km/h). This suggests that the effect of centrifugal forces, which are major on roundabouts with small diameter and minor on roundabouts with big diameter, lead bicyclists to ride slower on roundabouts with small diameter and faster on roundabouts with big diameter. Figure 3-a shows the percentage of free-flow bicyclists for the four ranges of speed differentiated for roundabouts with big and small diameter.

Table 3 – Mean values of free-flow bicyclists' speed and normalized distance (lateral position).

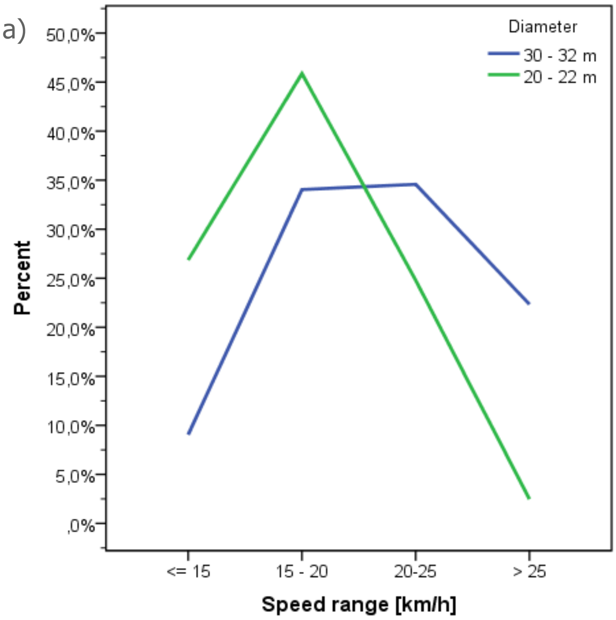
	Big diameter	Small diameter
Overall mean speed (s_{mean})		
1. Free-flow bicyclists (no interaction)	21.16 km/h	17.55 km/h
Overall mean normalized distance (N_{d_mean})		
1. Free-flow bicyclists (no interaction)	0.63 (zone 4)	0.55 (zone 3)

Table 4 – ANOVA tests for free-flow bicyclists' speed and normalized distance (lateral position).

	Mean square	F	p-value
ANOVA dependent variable: speed range			
Diameter	76.856	112.074	<0.001
ANOVA dependent variable: normalized distance			
Diameter	0.720	15.637	<0.001

The ANOVA test for normalized distance (Table 4) shows that normalized distance is also significantly different between the two different diameters (p=0.000<0.05). Looking at the mean values of normalized distance (Table 3) it can be seen that free-flow bicyclists ride closer to the central island on roundabouts with big diameter (N_{d_mean}=0.63, corresponding to zone 4) compared to roundabouts with small diameter (N_{d_mean} =0.55, corresponding to zone 3). Figure 3-b shows the percentage of free-flow bicyclists for the five zones of lateral position differentiated for roundabouts with big and small diameter. The lateral position and more in general the trajectory close to the external edge of the circulatory roadway is more constraining for bicyclists because it is associated to major resistance. Figure 3-b shows that free-flow bicyclists are not inclined to assume the most constraining lateral position, i.e. the one close to the external edge of the circulatory roadway (zone 1) both for small and big diameter. At the same time, very few free-flow bicyclists choose the most internal lateral position (zone 5) both for small and big diameter. This is probably due to the fact that bicyclists don't feel safe and confident riding too close to the central island. The majority of free-flow bicyclists chooses zone 3 for roundabouts with small diameter (40.1%) and zone 4 for roundabouts with big diameter (45.7%). We can therefore conclude that free-flow bicyclists rarely choose the most inner and the most outer part of the circulatory roadway.

a)



b)

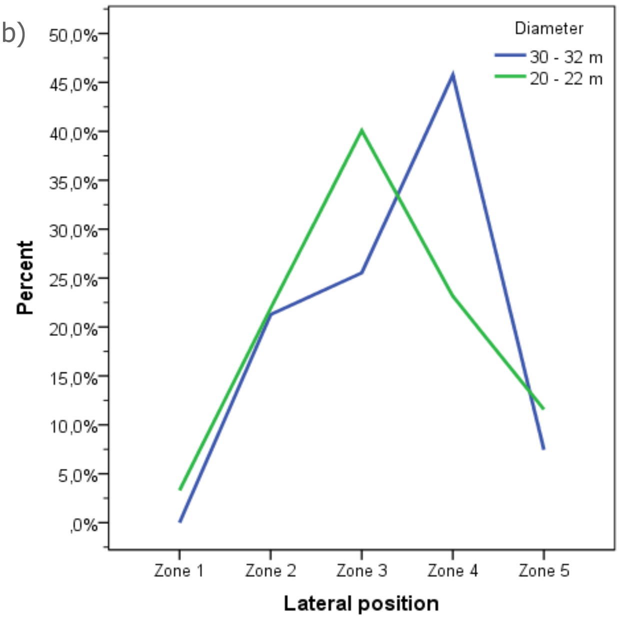


Figure 3 – a) Speed range of free-flow bicyclists for roundabouts with big diameter (30-32 m) and small diameter (20-22 m); b) Lateral position of free-flow bicyclists for roundabouts with big diameter (30-32 m) and small diameter (20-22 m).

5.1.2 Behavioural aspects of bicyclist-vehicle interactions

To answer the question of whether bicyclists' behaviour varies on roundabouts without bicycle facilities with regard to the diameter of the roundabout and of how the presence of a vehicle affect bicyclists' behaviour when riding on a roundabout without bicycle facilities, two univariate analyses of variance (ANOVA) are conducted considering both free-flow bicyclists and bicyclist-vehicle interactions. Conditions n. 4, 5, 6, 7 (i.e. *overtaking interactions – vehicle, overtaking interactions - bicyclists, entering interactions - vehicle enters first* and *entering interactions - bicyclist enters first*) are not considered for this analysis because they are less than 6% of the total sample (see Table 2). The total sample considered for these ANOVA analyses is therefore 874 situations, 444 of which are bicyclist-vehicle interactions (conditions 2, 3, 8, 9 in Table 2) and 430 are free-flow bicyclists (condition 1 in Table 2).

The dependent variables are the bicyclists' riding speed for the first ANOVA and the lateral position in the middle of the quadrant for the second one. Riding speed in the middle of the quadrant is expressed in km/h and is subdivided in four ranges (i.e. *≤15 km/h*, *15-20 km/h*, *20-25 km/h*, *>25 km/h*). Lateral position in the middle of the quadrant is expressed as normalized distance from the edge of the circulatory roadway. The independent variables are for both ANOVAs the diameter of the roundabout (*big diameter* or *small diameter*) and the condition (*1. Free-flow bicyclists (no interaction)*, *2. Following interactions - vehicle*, *3. Following interactions - bicyclist*, *8. Entering interactions - vehicle doesn't enter first, 9. Entering interactions - bicyclist doesn't enter first*). For all analyses the p-value was set at 0.05 to determine statistical significance.

Table 5 shows the mean values of bicyclists' and lateral position. Table 6 shows the results of the ANOVA tests for bicyclists' speed and speed lateral position.

The ANOVA test for speed (Table 6) shows that speed is significantly different between the two different diameters ($p<0.001$). Looking at the mean values of speed (Table 5) and at Figure 4-a we can see that bicyclists ride significantly faster on roundabouts with big diameter compared to roundabouts with small diameter for all the conditions analysed. This means that, regardless of the type of condition (free-flow or different interactions), bicyclists always ride faster on roundabouts with big diameter and slower on roundabouts with small diameter. This supports what we already observed in paragraph 5.1., i.e. that the effect of centrifugal forces, which are major on roundabouts with small diameter and minor on roundabouts with big diameter, lead bicyclists to ride slower on roundabouts with small diameter and faster on roundabouts with big diameter.

Table 5 – Mean values of bicyclists' speed and normalized distance (lateral position) for all conditions.

	Big diameter	Small diameter
Overall mean speed (s_{mean})		
1. Free-flow bicyclists (no interaction)	21.16	17.55
2. Following interactions - vehicle	18.71	16.40
3. Following interactions - bicyclist	20.19	16.94
8. Entering interactions - vehicle doesn't enter first	20.84	16.93
9. Entering interactions - bicyclist doesn't enter first	15.82	13.07
Overall mean normalized distance (N_{d_mean})		
1. Free-flow bicyclists (no interaction)	0.63	0.55
2. Following interactions - vehicle	0.55	0.51
3. Following interactions - bicyclist	0.59	0.55
8. Entering interactions - vehicle doesn't enter first	0.63	0.55
9. Entering interactions - bicyclist doesn't enter first	0.56	0.54

Table 6 – ANOVA tests for bicyclists' speed and normalized distance (lateral position) for all conditions.

	Mean square	F	p-value
ANOVA dependent variable: speed range			
Diameter	54.179	88.011	<0.001
Condition	15.814	25.690	<0.001
ANOVA dependent variable: normalized distance			
Diameter	0.428	9.349	0.002
Condition	0.137	3.002	0.018

The ANOVA test for normalized distance (Table 6) shows that normalized distance is significantly different between the two different diameters ($p=0.002<0.05$). The mean values of normalized distance (Table 5) and Figure 4-a show that bicyclists ride closer to the central island on roundabouts with big diameter ($N_{d\_mean}=0.63$, corresponding to zone 4) compared to roundabouts with small diameter ($N_{d\_mean}=0.55$, corresponding to zone 3) for all the conditions analysed. Regardless of the type of condition (free-flow or different interactions), bicyclists therefore ride closer to the central island on roundabouts with big diameter. We can therefore conclude that bicyclists rarely choose the most inner and the most outer part of the circulatory roadway.

The ANOVA tests for speed and for lateral position (Table 6) show that speed and lateral position are also significantly different among the different conditions ($p<0.001$ for speed and $p=0.018<0.05$ for lateral position). Figure 4-a and b) shows the mean values of speed of bicyclists for each condition differentiated for big and small diameter. By comparing speed and lateral position of free-flow bicyclists with speed and lateral position of each type of interaction it is possible to understand how the different types of interactions affect the behaviour of bicyclists. The interactions affecting bicyclists behaviour more strongly both in terms of speed and lateral position are *following interactions – vehicle* (condition 2) and *entering interactions – bicyclist doesn't enter first* (condition 9).

E*ntering interaction – bicyclist doesn't enter first* (condition 9) is of course strongly conditioning in terms of speed because the bicyclists is entering the roundabout and his speed is therefore definitely lower than the free-flow case. Table 5 and Figure 4-a show that for both big and small diameters the mean speed of interactions 7 (15.82 km/h and 13.07 km/h respectively) is lower than the mean speed of free-flow bicyclists (21.16 km/h and 17.55 km/h respectively). Table 5 and Figure 4-b show that for both big and small diameters also the mean normalized distance of interactions 9 (0.56 and 0.54 respectively) is lower than the mean normalized distance of free-flow bicyclists (0.63 and 0.55 respectively). This suggests that bicyclists entering the roundabout are naturally more inclined to ride closer to the external edge of the circulatory roadway. It is however essential to note that the lower values of speed and normalized distance are due to the type of manoeuvre (entering manoeuvre) rather than to the vehicle's influence.

Following interaction – vehicle (condition 2) definitely seems to be the type of interaction mostly affecting the behaviour of bicyclists from a psychological point of view. During this type of interaction, a vehicle is driving behind a bicyclist on the circulatory roadway. The bicyclist is therefore riding on the circulatory roadway and is not doing manoeuvres which could affect his speed or his lateral position. The only element that can affect his behaviour is the presence of the following vehicle. Table 5 and Figure 4-b show that for both big and small diameters the mean normalized distance of interactions 2 (0.55 and 0.51 respectively) is lower than the mean normalized distance of free-flow bicyclists (0.63 and 0.55 respectively). Figure 5 shows the percentage of bicyclists for condition 2 (*following interactions – vehicle*) for the five zones of lateral position differentiated for roundabouts with big and small diameter. From the comparison of Figure 5 and Figure 3-b it can be seen that for big diameter the majority of free-flow bicyclists rides on zone 4 (45.7%) while the majority of bicyclists who are followed by a vehicle rides on zone 3 (42.5%). In the same way, for small diameter the majority of free-flow bicyclists rides on zone 3 (40.1%) while the majority of bicyclists who are followed by a vehicle is distributed on zone 2 and zone 3 (34.5% and 35.7% respectively). This suggests that bicyclists are strongly conditioned by the presence of the following vehicle in roundabouts and are therefore inclined to ride closer to the external edge of the circulatory roadway, both for roundabouts with big and small diameter. This is probably due to the fact that bicyclists don't feel confident and safe while followed by a vehicle and tend therefore to assume a more external position in order to favour the overtaking. Since bicyclists tend to assume a more external lateral position, the resulting trajectories on the circulatory roadway are likely longer and have a higher curvature compared to the trajectories of free-flow bicyclists. This obviously results in a reduction of speed, which is confirmed by Table 5 and Figure 4-a. We can indeed observe that for both big and small diameters the mean speed of interactions 2 (18.71 km/h and 16.40 km/h respectively) is lower than the mean speed of free-flow bicyclists (21.16 km/h and 17.55 km/h respectively). It seems that the reduction of speed and normalized distance associated to interactions 2 is higher for roundabouts with big diameter rather than for roundabouts with small diameter. Mean speed difference between free-flow bicyclists and interactions 2 is indeed 2.41 km/h for big diameter and 1.15 km/h for small diameter. In the same way, normalized distance difference between free-flow bicyclists and interactions 2 is 0.08 for big diameter (corresponding to the switch from zone 4 to zone 3) and 0.04 for small diameter (corresponding to the shift to the most external part of zone 3). This suggests that bicyclists feel more confident on roundabouts with small diameter and are therefore able to deal better with the presence of a following vehicle.

Following interactions – bicyclist (condition 3) and *Entering interactions - vehicle doesn't enter first* (condition 8) do not seem to affect bicyclists' speed and lateral position. Mean speed of interactions 3 and 8 are indeed very similar to mean speed of free-flow bicyclists both for roundabouts with big and small diameter (see Table 5 and Figure 4-a). At the same time, mean normalized distance of interactions 3 and 8 are very similar to mean normalized distance of free-flow bicyclists both for roundabouts with big and small diameter (see Table 5 and Figure 4-b. The presence of a vehicle preceding the bicyclist on the circulatory roadway (interaction 3) or the presence of a vehicle entering the roundabout after the bicyclist (interaction 8) does not seem to affect bicyclists' behaviour.

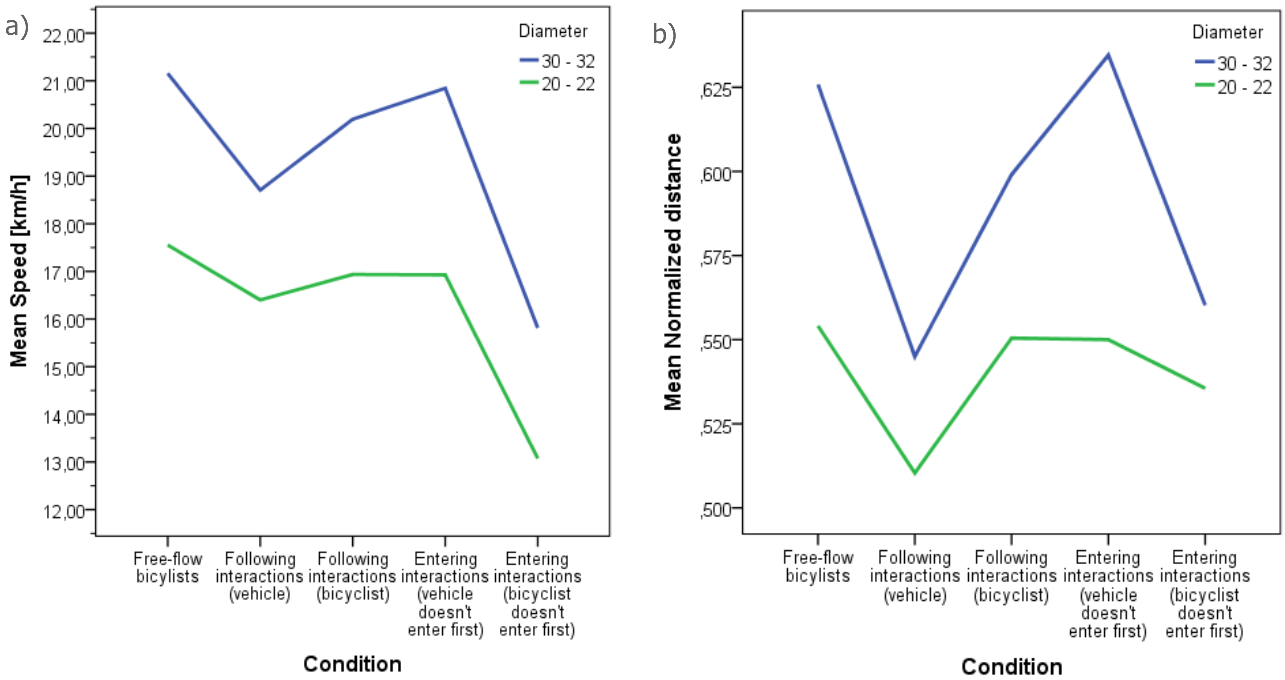


Figure 4 – a) Mean speed of bicyclists for each condition for roundabouts with big diameter (30-32 m) and small diameter (20-22 m); b) Mean normalized distance for each condition for roundabouts with big diameter (30-32 m) and small diameter (20-22 m).

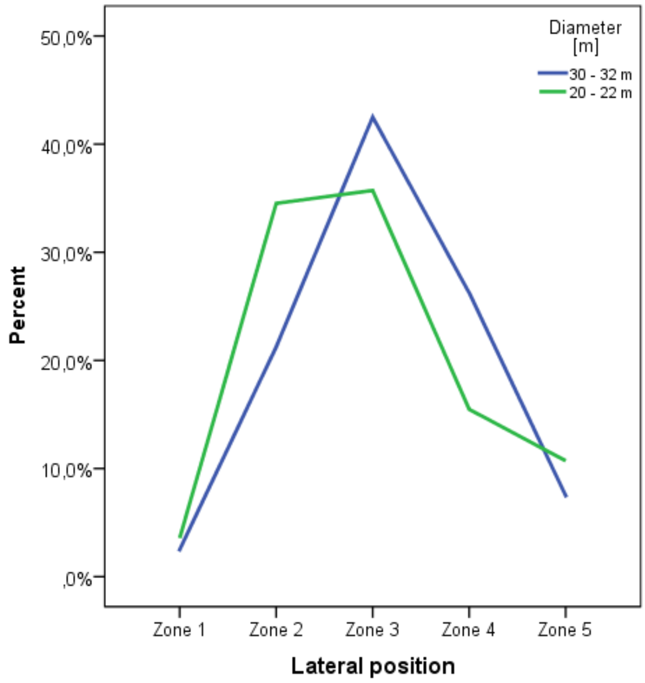


Figure 5 – Lateral position of bicyclists for interactions 2 (*following interactions – vehicle*) for roundabouts with big diameter (30-32 m) and small diameter (20-22 m).

5.2 Occurrence of close interactions

5.2.1 Surrogate safety indicators

Surrogate safety indicators were calculated for all interactions that had a relatively high subjective level of unsafety, with enough safety margin to ascertain that none of the truly severe situations were missed. A total of 123 interactions were selected from the analyses of 16+16 hours of video for each roundabout (Video Analysis 1 and Video Analysis 2) for the calculation of surrogate safety indicators. The number of interactions preselected for the analysis of surrogate safety indicators is similar for roundabouts with big diameter (64 interactions) and with small diameter (59 interactions).

Sections 5.2.1.1, 5.2.1.2 and 5.2.1.3 report, respectively, the number of observed events with TTC_{min}, PET and $T_{2\ min}$ below the threshold values. Section 5.2.1.4 show then the number of observed events for which at least one of the surrogate safety indicators considered (TTC, PET, T_2) has a value below the threshold value. The percentages of observed events always refer to the total amount of interactions observed during the whole video analysis, i.e. the analysis of 16+16 hours of video for each roundabout (N_b=560 for roundabouts with big diameter; N_s=522 for roundabouts with small diameter; N_t=1,082 in total). Since Video Analysis 2 was aimed only at the identification of close interactions, the total amount of observed interactions for Video Analysis 2 was not known. The number of interactions for Video Analysis 2 was therefore estimated based on the number of interactions observed for Video Analysis 1, i.e. for each roundabout the number of interactions observed for a certain one-hour time slot on a certain day was assumed to be equal for Video Analysis 1 and 2.

5.2.1.1 TTC_{min}

Table 7 shows the type and the number of observed bicyclist-vehicle interactions with TTC_{min} below the threshold of 1.5 s on both roundabouts with big and small diameter. It can be seen that, based on TTC_{min}, very few close interactions were observed. On the roundabouts with small diameter, 6 events have a TTC_{min} less than 1.5 s, corresponding to 1.15% of the total amount of interactions for small roundabouts. On the roundabouts with big diameter, no close interactions have a TTC_{min} less than 1.5 s. Fisher's Exact Test shows that the proportion of interactions with a TTC_{min} below the threshold value is significantly different between both locations (threshold <1.5 s: $p = 0.012<0.05$).

Table 7 – Number and type of observed interactions with TTC_{min}<1.5 s for roundabouts with big diameter (roundabouts 1 and 3) and roundabouts with small diameter (roundabouts 2 and 4).

Condition	Big diameter		Small diameter		Total	
	Count	Percent*	Count	Percent*	Count	Percent*
2. Following interactions - vehicle	0	0.00	0	0.00	0	0.00
3. Following interactions - bicyclist	0	0.00	0	0.00	0	0.00
4. Overtaking interactions - vehicle	0	0.00	0	0.00	0	0.00
5. Overtaking interactions - bicyclist	0	0.00	0	0.00	0	0.00
6. Entering interactions - vehicle enters first	0	0.00	1	0.19	1	0.09
7. Entering interactions - bicyclist enters first	0	0.00	0	0.00	0	0.00
8. Entering interactions - vehicle doesn't enter first	0	0.00	2	0.38	2	0.18
9. Entering interactions - bicyclist doesn't enter first	0	0.00	3	0.57	3	0.28
Total	0	0.00	6	1.15	6	0.55

* Percentage of events are based on the total amount of interactions related to the whole video analysis (N_b=560 for roundabouts with big diameter; N_s=522 for roundabouts with small diameter; N_t=1,082 for the total)

5.2.1.2 PET

Table 8 shows the type and the number of observed bicyclist-vehicle interactions with PET below the threshold of 1 s on both roundabouts with big and small diameter. It can be seen that the number of interactions that have a PET lower than 1 s is quite high. On the roundabouts with big diameter, 39 interactions have a PET less than 1 s, corresponding to 6.96% of the total amount of interactions for big roundabouts. On the small roundabouts, 32 interactions have a PET less than 1 s, corresponding to 6.13% of the total amount of interactions for small roundabouts. The most common type of close interactions on roundabouts with big diameter are *Following interactions – bicyclist* (1.96%), while the most common type of close interactions on roundabouts with small diameter are *Entering interactions - bicyclist doesn't enter first* (3.07%). Chi Square Test shows that the proportion of interactions with a PET below the threshold value does not significantly differ between both locations (threshold <1 s: $\chi^2(1) = 0.306$; p = 0.580>0.05).

Table 8 – Number and type of observed interactions with PET<1 s for roundabouts with big diameter (roundabouts 1 and 3) and roundabouts with small diameter (roundabouts 2 and 4).

Condition	Big diameter		Small diameter		Total	
	Count	Percent*	Count	Percent*	Count	Percent*
2. Following interactions - vehicle	3	0.54	6	1.15	9	0.83
3. Following interactions - bicyclist	11	1.96	1	0.19	12	1.11
4. Overtaking interactions - vehicle	1	0.18	0	0.00	1	0.09
5. Overtaking interactions - bicyclist	2	0.36	1	0.19	3	0.28
6. Entering interactions - vehicle enters first	3	0.54	3	0.57	6	0.55
7. Entering interactions - bicyclist enters first	7	1.25	5	0.96	12	1.11
8. Entering interactions - vehicle doesn't enter first	5	0.89	0	0.00	5	0.46
9. Entering interactions - bicyclist doesn't enter first	7	1.25	16	3.07	23	2.13
Total	39	6.96	32	6.13	71	6.56

* Percentage of events are based on the total amount of interactions related to the whole video analysis (N_b=560 for roundabouts with big diameter; N_s=522 for roundabouts with small diameter; N_t=1,082 for the total)

5.2.1.3 $T_{2\,min}$

Table 9 shows the type and the number of observed vehicle-bicycle interactions with $T_{2\,min}$ below the threshold of 1 s on both roundabouts with big and small diameter . It can be seen that the number of interactions that have a $T_{2\,min}$ lower than 1 s is quite high. On the roundabouts with big diameter 42 interactions have a $T_{2\,min}$ less than 1 s, corresponding to 7.50% of the total amount of interactions for big roundabouts. On the small roundabouts 38 interactions have a $T_{2\,min}$ less than 1 s, corresponding to 7.28% of the total amount of interactions for small roundabouts. The most common type of close interactions on roundabouts with big diameter are *Following interactions – bicyclist* (1.96%), while the most common type of close interactions on roundabouts with small diameter are *Entering interactions - bicyclist doesn't enter first* (3.64%). Chi Square Test shows that the proportion of interactions with a $T_{2\,min}$ below the threshold value does not significantly differ between both locations (threshold <1 s: $\chi 2(1) = 0.019$; $p = 0.890>0.05$). These results are in line with those of PET, also in terms of most frequent types of close interactions.

Table 9 – Number and type of observed interactions with $T_{2\,min}$ <1 s for roundabouts with big diameter (roundabouts 1 and 3) and roundabouts with small diameter (roundabouts 2 and 4).

Condition	Big diameter		Small diameter		Total	
	Count	Percent*	Count	Percent*	Count	Percent*
2. Following interactions - vehicle	3	0.54	7	1.34	10	0.92
3. Following interactions - bicyclist	11	1.96	1	0.19	12	1.11
4. Overtaking interactions - vehicle	2	0.36	0	0.00	2	0.18
5. Overtaking interactions - bicyclist	2	0.36	1	0.19	3	0.28
6. Entering interactions - vehicle enters first	3	0.54	3	0.57	6	0.55
7. Entering interactions - bicyclist enters first	8	1.43	5	0.96	13	1.20
8. Entering interactions - vehicle doesn't enter first	4	0.71	2	0.38	6	0.55
9. Entering interactions - bicyclist doesn't enter first	9	1.61	19	3.64	28	2.59
Total	42	7.50	38	7.28	80	7.39

* Percentage of events are based on the total amount of interactions related to the whole video analysis (N_b=560 for roundabouts with big diameter; N_s=522 for roundabouts with small diameter; N_t=1,082 for the total)

5.2.1.4 Summary analysis of surrogate safety indicators

Each vehicle-bicycle interaction for which at least one of the surrogate safety indicators considered (TTC_{min}, PET, $T_{2\,min}$) had a value below the threshold value can be considered a close interaction. In total, 87 close interactions were identified from the analysis of 16+16 hours of video for each roundabout (Video Analysis 1 and Video Analysis 2) corresponding to 8.04% of all interactions.

The 6 situations indicated as severe by TTC_{min} are all considered severe by $T_{2\,min}$ and all but two by PET as well. 69 situations are considered severe by both $T_{2\,min}$ and PET. Moreover, all but seven situations indicated as severe by PET are considered severe by $T_{2\,min}$.

Table 10 shows the type and the number of observed close interactions for roundabouts with big diameter (i.e. roundabouts 1 and 3) and for roundabouts with small diameter (i.e. roundabouts 2 and 4). The percentages of close interactions are comparable for roundabouts with big diameter (7.86%) and roundabouts with small diameter (8.24%).

The most common type of close interactions at the big roundabouts are *Following interactions – bicyclist* (2.14%), *Entering interactions – bicyclist doesn't enter first* (0.89%) and *Entering interactions – bicyclist enters first* (1.43%). The most common type of close interactions at the small roundabouts are *Entering interactions – bicyclist doesn't enter first* (3.83%), *Following interactions vehicle* (1.72%) and *Entering interactions – bicyclist enters first* (1.15%).

Table 10 – Number of observed close interactions for roundabouts with big diameter (roundabouts 1 and 3) and roundabouts with small diameter (roundabouts 2 and 4).

Condition	Big diameter		Small diameter		Total	
	Count	Percent*	Count	Percent*	Count	Percent*
2. Following interactions - vehicle	3	0.54	9	1.72	12	1.11
3. Following interactions - bicyclist	12	2.14	1	0.19	13	1.20
4. Overtaking interactions - vehicle	2	0.36	0	0.00	2	0.18
5. Overtaking interactions - bicyclist	2	0.36	1	0.19	3	0.28
6. Entering interactions - vehicle enters first	3	0.54	3	0.57	6	0.55
7. Entering interactions - bicyclist enters first	8	1.43	6	1.15	14	1.29
8. Entering interactions - vehicle doesn't enter first	5	0.89	3	0.57	8	0.74
9. Entering interactions - bicyclist doesn't enter first	9	1.61	20	3.83	29	2.68
Total	44	7.86	43	8.24	87	8.04

* Percentage of events are based on the total amount of interactions related to the whole video analysis (N_b=560 for roundabouts with big diameter; N_s=522 for roundabouts with small diameter; N_t=1,082 for the total)

Chi Square Test shows that the proportion of close interactions identified does not significantly differ between both locations ($\chi^2(1) = 0.053$; $p = 0.818>0.05$). The Chi Square test or the Fisher Test was also performed for each type of close interaction. The results of the tests show the proportion of close interactions 2, 4, 5, 6, 7, 8 does not significantly differ between big and small roundabouts (p=0.104, p=0.688, p=0.728, p=0.582, p=0.967, p=0.456 respectively), while the proportion of close interactions 3 and 9 is significantly different between both locations (p=0.003 and p=0.040 respectively).

Looking at the total number of close interactions (for both big and small roundabouts), it can be seen that the most common types of close interactions are *Entering interactions – bicyclist doesn't enter first* (2.68%) and *Entering interactions – bicyclist enters first* (1.29%). The most common types of close interactions are therefore interactions where the bicyclist is entering the roundabout. This seems to suggest that the most dangerous situations for a bicyclist riding a roundabout occur when he/she has to enter the roundabout.

5.2.2 Lateral overtaking proximity

Table 11 shows the observed *lateral overtaking proximity* of *Overtaking interactions – vehicle* (condition 4) and of *Overtaking interactions – bicyclist* (condition 5) on both roundabouts with big and small diameter obtained from the analysis of 16 hours of video for each roundabout (Video Analysis 1). The analysis of *lateral overtaking proximity* focuses on the hours of behavioural observations only (i.e. Video Analysis 1) because *lateral overtaking proximity* was measured for all overtaking events for those hours of video analysis.

The distribution of the *lateral overtaking proximity* for all interactions with overtaking of Video Analysis 1 on big and small roundabouts is shown in the box plots in Figure 6. The black line inside the box represents the median value and the sides of the boxes represent the upper and lower quartile values. The whiskers indicate the variability outside the upper and lower quartiles. The threshold value of 1 m is indicated by the red vertical line.

It can be seen that few overtaking interactions were observed and that most of them are on roundabouts with big diameter. Interactions where the vehicle overtakes a bicyclist (condition 4) are definitely more common on roundabouts with big diameter rather than on roundabouts with small diameter (respectively 10 and 2 events observed). *Overtaking interactions – bicyclist* (condition 5) are still more common on roundabouts with big diameter rather than on roundabouts with small diameter (respectively 5 and 3 events observed). *Lateral overtaking proximity* values of *Overtaking interactions – vehicle* (condition 4) are lower than 1 meter only for one event on roundabouts with big diameter. *Lateral overtaking proximity* values of *Overtaking interactions – vehicle* (condition 4) are lower than 1 meter for two events on roundabouts with big diameter and for one event on roundabouts with small diameter.

The box plots of Figure 6 also show that for *Overtaking interactions –vehicle* (condition 4) the median *lateral overtaking proximity* is slightly different for both big and small roundabouts (2.63 m and 2.29 m respectively). A higher dispersion of lateral overtaking proximities is however observed on the roundabouts with big diameter. For *Overtaking interactions –bicyclist* (condition 4) the median *lateral overtaking proximity* is similar for big and small roundabouts (1.17 m and 1.12 m respectively). It is interesting to observe that the lateral overtaking proximities of *Overtaking interactions – bicyclist* (condition 5) are smaller than lateral overtaking proximities of *Overtaking interactions – vehicle* (condition 4) for both small and big roundabouts. The proportion of *Overtaking interactions –vehicle* (condition 4) and of *Overtaking interactions –bicyclist* (condition 5) that have a *lateral overtaking proximity* of less than 1 m is however not significantly different between both big and small roundabouts (the Fisher test gives p=0.833 and p=0.714).

Table 11 – Distribution of *lateral overtaking proximity* for *overtaking interactions – vehicle* (condition [4]) and for *overtaking interactions – bicyclist* (condition [5]). (Left: roundabouts with big diameter (30-32 m); right: small diameter (20-22 m).

	4. Overtaking interactions - vehicle		5. Overtaking interactions - bicyclist	
	Big diameter	Small diameter	Big diameter	Small diameter
Number of overtaking interactions	10	2	5	3
Lateral overtaking proximity L_{op}				
Mean	2.44	2.29	1.48	1.28
Median	2.63	2.29	1.17	1.12
Max	3.79	2.44	2.56	1.92
Min	0.82	2.14	0.2	0.80
Number of overtaking interactions with L_{op} < 1 m	1	0	2	1

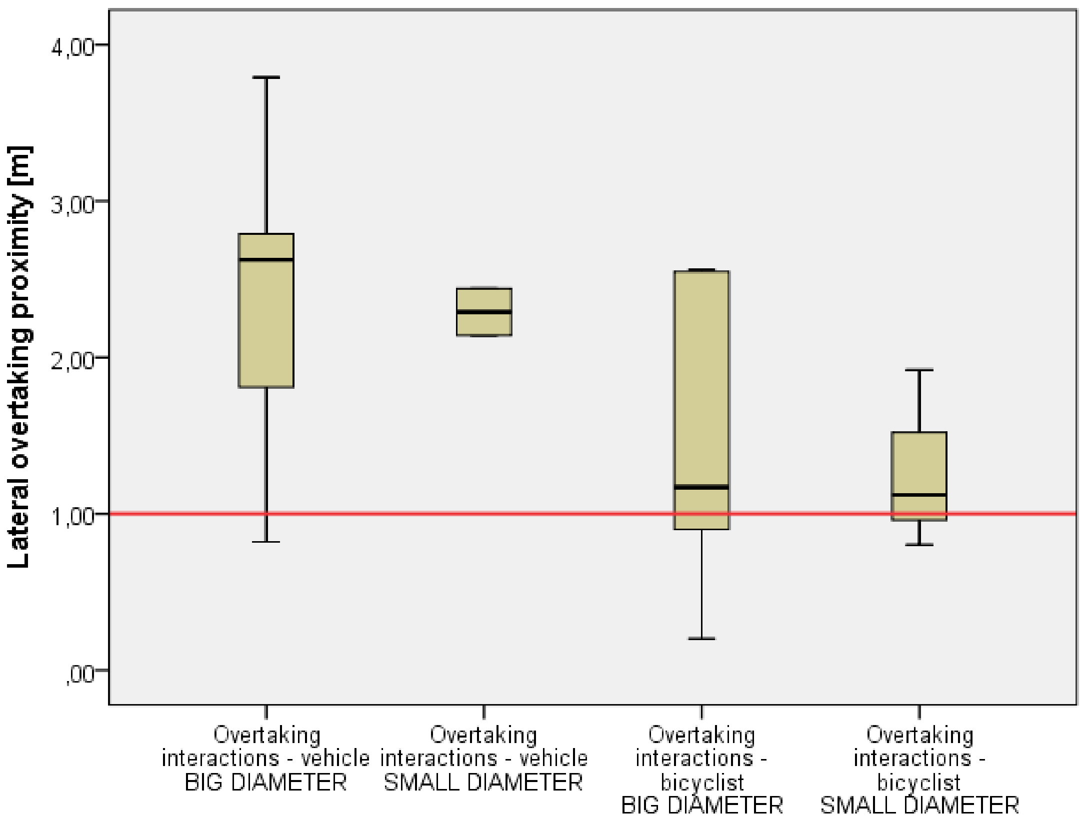


Figure 6 – Lateral overtaking proximity position of bicyclists for interactions 4 (*overtaking interactions – vehicle*) and for interactions 5 (*overtaking interactions – bicyclist*) for roundabouts with big diameter (30-32 m) and small diameter (20-22 m).

5.2.3 Minimum distance headway

Figure 7 shows histograms of the observed *minimum distance headway* values of *Following interactions – vehicle* (condition 2) on both roundabouts with big and small diameter obtained from the analysis of 16 hours of video for each roundabout (Video Analysis 1). Figure 8 shows histograms of the observed *minimum distance headway* values of *Following interactions – bicyclist* (condition 3) on both roundabouts with big and small diameter obtained from the analysis of 16 hours of video for each roundabout (Video Analysis 1). The *minimum distances headway* shown in Figure 7 and 8 are obtained from the analysis of 16 hours of video for each roundabout (Video Analysis 1). The analysis of *minimum distance headway* focuses indeed on the hours of behavioural observations because *minimum distance headway* was measured for all following events for those hours of video analysis.

By comparing the percentages of *minimum distances headway* below 3 meters of Figure 7 and Figure 8 it can be seen that bicyclists who follow a vehicle seem to take smaller following distances than cars following a bicycle. Moreover, Figure 8 shows that following distances for bicyclists who follow a vehicle are smaller at the small roundabouts (the *minimum distances headway* below 3 meters are 12% for roundabouts with big diameter, while the *minimum distances headway* below 3 meters are 32% for roundabouts with small diameter). Anyway these considerations have to be carefully considered since speed is not taken into account. It is the combined effect of speed and distance (i.e. the time gap) which gives a better measurement of the closeness of following interactions.

The proportion of *Following interactions –vehicle* (condition 2) and of *Following interactions –bicyclist* (condition 3) that have a *minimum distance headway* of less than 3 m is however not significantly different between both big and small roundabouts (the Fisher test gives respectively p=0.219 and p=0.500).

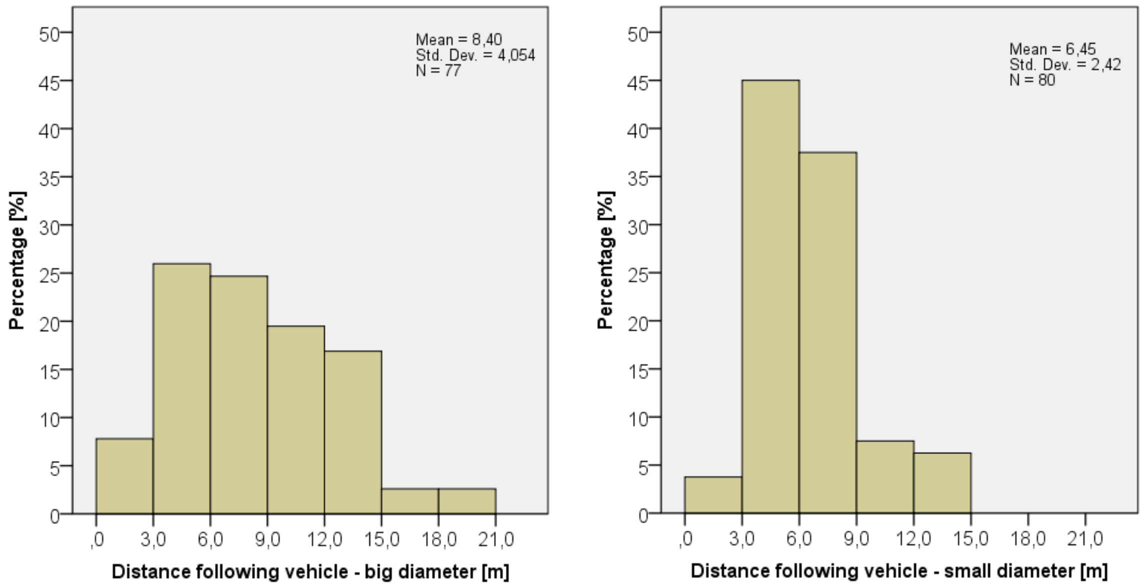


Figure 7 – Distribution of minimum distance headway values for following interactions – vehicle (condition 2). (Left: roundabouts with big diameter (30-32 m); right: small diameter (20-22 m).

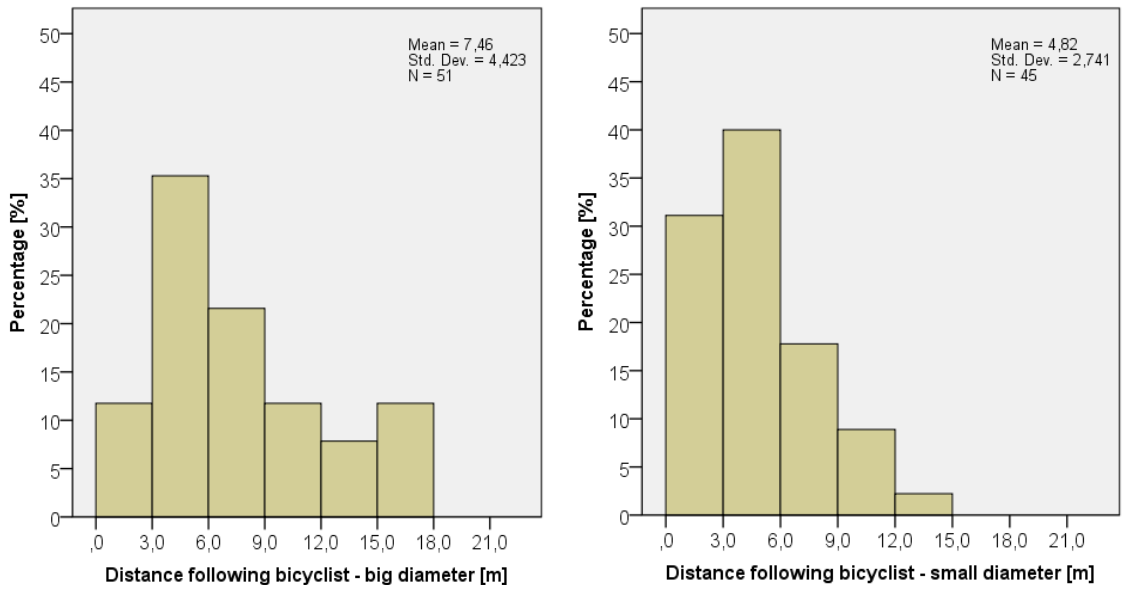


Figure 8 – Distribution of minimum distance headway values for following interactions – bicyclist (condition 3). (Left: roundabouts with big diameter (30-32 m); right: small diameter (20-22 m).

6. Conclusions

Observations at four urban roundabouts without bicycle facilities with different diameter allowed to evaluate how the diameter affect behavioural and surrogate safety indicators of bicyclists interacting with vehicles. The behavioural analysis revealed that regardless of the type of condition (free-flow bicyclists or different interactions bicyclist-car), bicyclists always ride faster on roundabouts with big diameter and slower on roundabouts with small diameter. Moreover, bicyclists ride closer to the central island on roundabouts with big diameter compared to roundabouts with small diameter for all the conditions analysed. Bicyclists who are followed by a vehicle are indeed inclined to ride closer to the external edge of the circulatory roadway, both for roundabouts with big and small diameter. It seems that the reduction of speed and normalized distance associated to interactions 2 is higher for roundabouts with big diameter rather than for roundabouts with small diameter.

The analysis of surrogate safety indicators revealed that close interactions between bicyclists and cars are relatively frequent at both small and big roundabouts. *Time to collision* (TTC), *Post-Encroachment-Time* (PET) and *T2-value* were calculated for all interactions that had a relatively high subjective level of unsafety. Each vehicle-bicycle interaction for which at least one of the surrogate safety indicators considered had a value below the threshold value was considered a close interaction. This allowed to identify 87 close interactions, corresponding to 8.04% of all interactions. The percentages of close interactions are more or less equal for roundabouts with big diameter (7.86%) and roundabouts with small diameter (8.24%). The most common types of close interactions for all the roundabouts analysed are *Entering interactions – bicyclist doesn't enter first* (2.68%) and *Entering interactions – bicyclist enters first* (1.29%). This seems to suggest that the most dangerous situations for a bicyclist at a roundabout occur when he/she has to enter the roundabout.

Few overtaking interactions were observed and most of them are on roundabouts with big diameter. Interactions where the vehicle overtakes a bicyclist (condition 4) are more common on roundabouts with big diameter rather than on roundabouts with small diameter. *Overtaking interactions – bicyclist* (condition 5) are still more common on roundabouts with big diameter than on roundabouts with small diameter. Lateral overtaking proximities of *Overtaking interactions – bicyclist* (condition 5) are smaller than lateral overtaking proximities of *Overtaking interactions – vehicle* (condition 4) for both small and big roundabouts. The analysis of minimum distances headway for *Following interactions – vehicle* (condition 2) and for *Following interactions – bicyclist* (condition 3) revealed that bicyclists who follow a vehicle seems to take smaller following distances than cars following a bicycle.

In conclusion the analysis of the indicators to describe the closeness of interactions (TTC_{min}, PET, $T_{2\ min}$, lateral overtaking proximity and minimum distance headway) showed that the majority of close interactions at roundabouts are situations where the bicyclist has a leading role. The analysis of the most common types of close interactions revealed indeed that the most common close interactions are interactions where the bicyclist is entering the roundabout. The analysis of lateral overtaking proximity showed that bicyclists who overtake a car take smaller lateral overtaking proximities compared to cars overtaking a bicyclist. The analysis of minimum distance headway finally revealed that bicyclists who ride behind a car take smaller minimum distances headway compared to cars driving behind a bicyclist. This suggests that bicyclists are more aware of their dimensions and they tend therefore to ride closer to cars at roundabouts. This could more easily evolve into dangerous situations.

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Institut Vias
Haachtsesteenweg 1405, 1130 Brussel · Chaussée de Haecht 1405, 1130 Bruxelles · +32 2 244 15 11 · info@vias.be · www.vias.be