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Safety of bicyclists in roundabouts with mixed traffic: Video analyses of behavioural and surrogate safety indicators

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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.

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1. Introduction

Although converting an intersection into a roundabout has been shown to result in fewer injury accidents for both motor vehicle drivers and pedestrians (Canale, Distefano, & Leonardi, 2015; Elvik & Vaa, 2009; Hydén & Várhelyi, 2000; NCHRP, 2007; Retting, Persaud, Garder, & Lord, 2001), the effect on bicyclists' safety is unclear or even negative (Daniels, Nuyts, & Wets, 2008). Several studies have already focused on bicyclists' safety at roundabouts (Akgün, Dissanayake, Thorpe, & Bell, 2018; Hollenstein, Hess, Jordan, & Bleisch, 2019; Jensen, 2017) but little is known about the interactions between bicyclists and other road vehicles at roundabouts where there are no dedicated bicycle facilities. Better understanding of how bicyclists move and interact with other vehicles at roundabouts without bicycle facilities is essential for improving bicyclists' safety.

Various studies have examined the public opinion on roundabouts and demonstrated that road users are generally favourable to roundabouts (Distefano et al., 2018, 2019; Leonardi, Distefano, & Pulvirenti, 2019; Richard A. Retting, Luttrell, & Russell, 2002). Over the last decades several studies have been carried out on the effects of roundabouts on traffic safety. Previous studies reported a considerable decrease in the number of accidents in roundabouts compared to standard intersections (De Brabander, Nuyts, & Vereeck, 2005; Elvik, 2003; Persaud, Retting, Garder, & Lord, 2001). Less is known about the safety effects of roundabouts for particular types of road users, such as bicyclists (Daniels & Wets, 2005). A Belgian study found that the conversion of intersections into 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 & Vereeck, 2007). However, Jensen (2017) stated that in high speed limit locations, converting intersections to single lane roundabouts decreases the number and the gravity of crashes for bicyclists.

Previous studies show that 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. Previous research also shows that an ample deflection angle at the entry/exit legs of roundabouts reduces vehicle speed which enhances cycling safety (Räsänen & Summala, 2000). 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, Brijs, Nuyts, and Wets (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. (Sakshaug, Laureshyn, Svensson, & Hydén, 2010) investigated different design solutions for bicyclists in roundabouts, namely, mixed traffic (i.e. without bicycle facilities) and separated cycle path. They found that mixed traffic conditions increased the number of conflicts as well as more serious conflicts between cyclists and vehicles. Møller and Hels (2008) studied bicyclists' risk perception in roundabouts. The results showed that an underestimation of risk and lack of knowledge about relevant traffic rules may contribute to car–bicycle collisions in roundabouts and that bicyclists prefer road designs with a clear regulation of road user behaviour.

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, Reid, Lester, Thomson, & Tolmie, 2002). On the other hand, bicyclists complain that driver behaviour ranges from dangerous to illegal (Chapman & 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, Bílová, & Müller, 2010; Chaurand & Delhomme, 2013; Matsui & Oikawa, 2015). The riskiest situation for bicyclists is interacting with a motorized vehicle (Bíl et al., 2010; Kim, Kim, Ulfarsson, & Porrello, 2007; Räsänen & Summala, 1998), particularly at an intersection (Carter, Hunter, Zegeer, Stewart, & Huang, 2007; Reynolds, Harris, Teschke, Cripton, & Winters, 2009; Wang & Nihan, 2004). For example, Kim et al., 2007 showed that>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 & Noyce, 2013; De Ceunynck et al., 2017; Love et al., 2012; Walker, Garrard, & Jowitt, 2014). Previous research showed how lateral clearance is influenced by infrastructure design (e.g. presence of bike lanes) (Chapman & Noyce, 2013; Frings, Parkin, & Ridley, 2014), the behaviour of the bicyclist (e.g. speed, steering angle, speed variation control) (Chuang, Hsu, Lai, Doong, & Jeng, 2013), the bicyclist's appearance (such as outfit, gender and helmet wearing) (Chuang et al., 2013; Walker, 2007; Walker et al., 2014), as well as by the drivers' characteristics (sensation seeking in flying overtaking manoeuvres and ordinary violations in accelerative manoeuvres) (Farah, Bianchi Piccinini, Itoh, & Dozza, 2019). 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, Sahlqvist, & Garrard, 2011).

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. This study can represent a starting point in the design and planning of roundabouts without bicycle facilities where bicyclists have to share the road with motorized vehicles. In order to explore the behaviour and the safety of bicyclists on roundabouts without bicycle facilities, the following research questions will be investigated:

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 what are the differences between roundabouts with a different diameter?

2. Methodology

2.1. 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 m approximately and two roundabouts have a diameter of 20 m approximately.

The first roundabout (Fig. 1 a) is located in the municipality of Zaventem. It has a diameter of 32 m. The second roundabout (Fig. 1 b) is located in the municipality of Woluwe-Saint-Lambert and has a diameter of 22 m. The third roundabout (Fig. 1 c) is located in the municipality of Woluwe-Saint-Lambert and has a diameter of 30 m. The fourth roundabout (Fig. 1 d) is located in the municipality of Ixelles and has a diameter of 20 m.

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 is only a difference in material. Because of this truck apron was considered part of the circulatory roadway width for roundabout 4.

2.2. 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 7:00p.m. for each roundabout (60 h 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, Cornu, 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).

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. The events were extracted manually from the videos. Interactions between bicyclists and vehicles different from passenger cars (i.e. buses, trucks, motorcycles, bicyclists) are really few

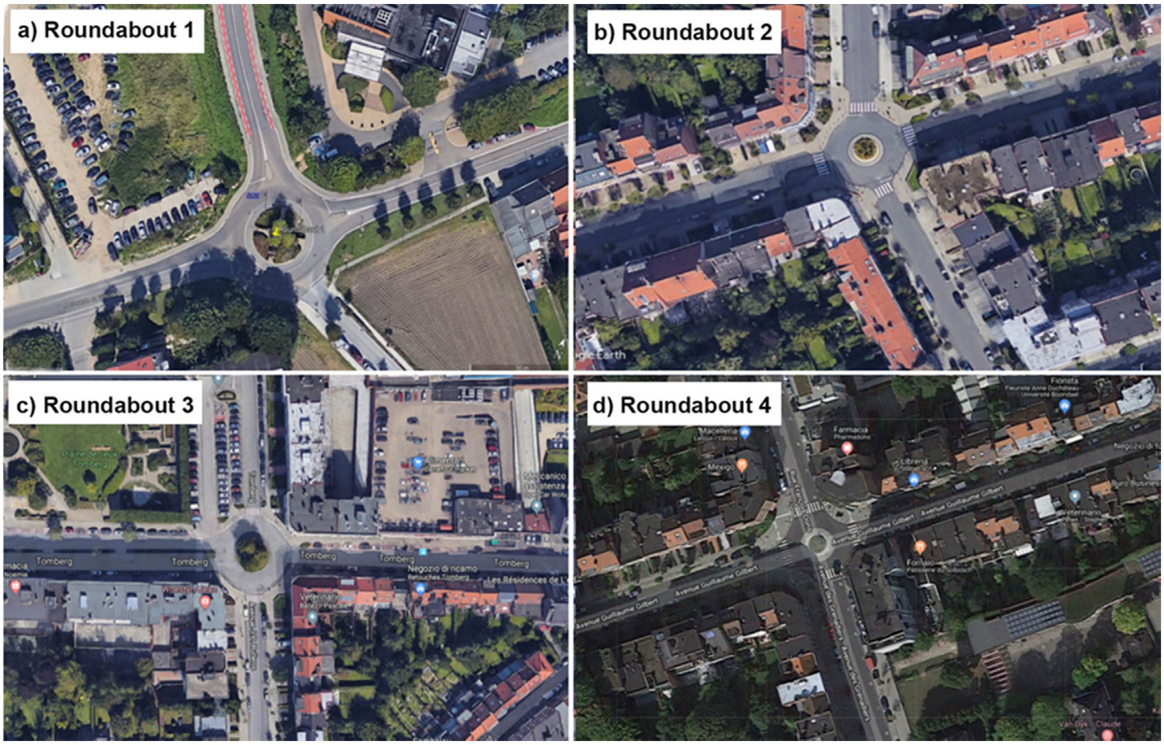

Fig. 1. Observation sites: a) Roundabout 1 (Zaventem – D = 32 m); b) Roundabout 2 (Woluwe-Saint-Lambert – D = 22 m); c) Roundabout 3 (Woluwe-Saint-Lambert– D = 30 m); d) Roundabout 4 (Ixelles – D = 20 m).

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

in number. The analysis developed in this paper regards therefore only free-flow bicyclists and interactions between bicyclists and passenger 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 × 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 × are equal to:

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

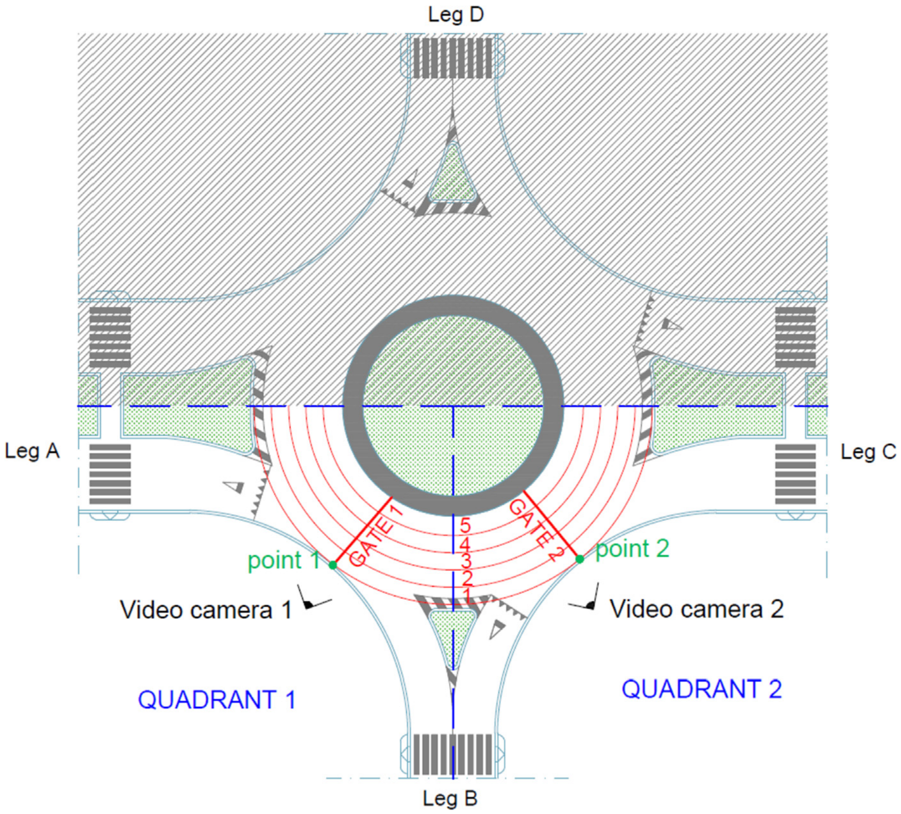

Fig. 2. Schematic representation of quadrants, video cameras position and gates.

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>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>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 × (obtained by multiplying the temporal intervals y and the speed z) are x = 20,53 m for the roundabouts with big diameter and x = 13.89 m for the roundabouts with small diameter, which are rounded respectively to x = 21 m and x = 14 m.

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)*.

Fig. 3 shows schematically the classification of interactions considered. For all interactions included, no other vehicles were present in quadrant 1 and quadrant 2 of the roundabout.

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 h 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 h 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.

2.3. Collected variables about behaviour

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

- Lateral position of the bicyclists in the middle of the quadrant, i.e. in the gates showed in Fig. 2; for each roundabout 5 zones are considered for lateral position, as shown in Fig. 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 Fig. 2; normalized distance is obtained by dividing the distance between the external edge of the circulatory roadway (point 1 and point 2 in Fig. 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: $0 < N_d \leq 0.2$ corresponds to zone 1; $0.2 < N_d \leq 0.4$ corresponds to zone 2; $0.4 < N_d \leq 0.6$ corresponds to zone 3; $0.6 < N_d \leq 0.8$ 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 Fig. 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.

The five variables related to bicyclists' behaviour were obtained by means of an analysis of each event (i.e. each free-flow bicyclist and each interactions between bicyclists and cars) using the software T-Analyst.

2.4. 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

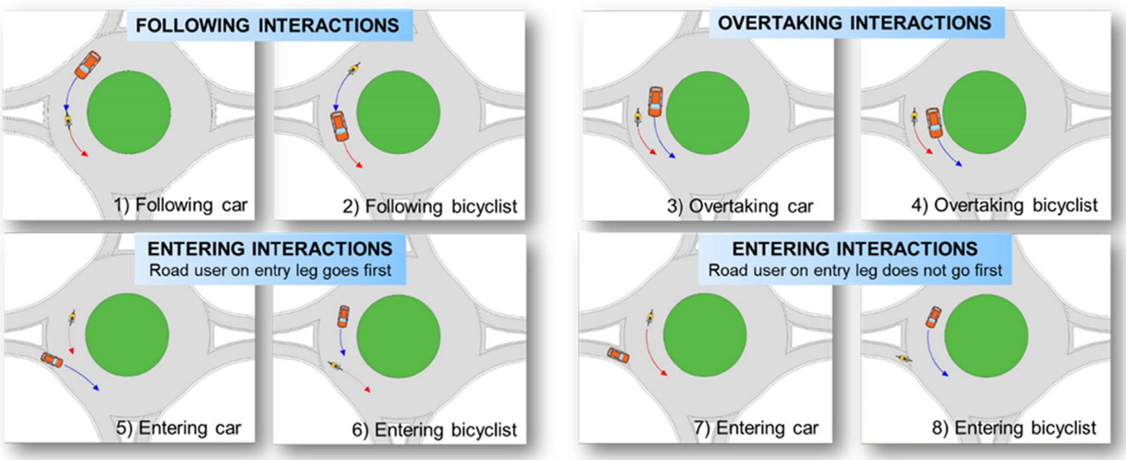

Fig. 3. Schematic representation of interactions.

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 (Johnsson, Laureshyn, & De Ceunynck, 2018; Laureshyn, de Goede, Saunier, & Fyhri, 2017). 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, 1994; Van Der Horst, 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 (Allen, Shin, & Cooper, 1978; Laureshyn, Svensson, & Hydén, 2010). All PET values lower than 1.0 s were considered close interactions based on scientific literature (Ismail, Sayed, Saunier, & Lim, 2009; Lakshmi 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 1 s 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 & 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. Since the four studied roundabouts are located inside built-up areas, overtaking manoeuvres with a *lateral overtaking proximity* of<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 & Wasielewski, 1982). Close-following is generally considered risky (Rajalin, Hassel, & Summala, 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.

The five indicators to describe the closeness of interactions were obtained by means of an analysis of each event (i.e. each free-flow bicyclist and each interactions between bicyclists and cars) using the software T-Analyst.

3. Results and discussion

3.1. Analysis of free-flow bicyclists and bicyclists-vehicle interactions

The database obtained from the analysis of 16 h 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.

3.1.1. 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 round-

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

about (*big diameter* or *small diameter*). For all analyses the p-value was set at 0.05 to determine statistical significance. The normal shape of the statistics was tested before running the ANOVA. The Kolmogorov-Smirnov test was satisfied (p-value > 0.05) for both speed and lateral position datasets. 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). Fig. 4-a shows the percentage of free-flow bicyclists for the four ranges of speed differentiated for roundabouts with big and small diameter.

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).

Fig. 4-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 (i.e. major centrifugal forces). Fig. 4-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 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.

3.1.2. 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 round-

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

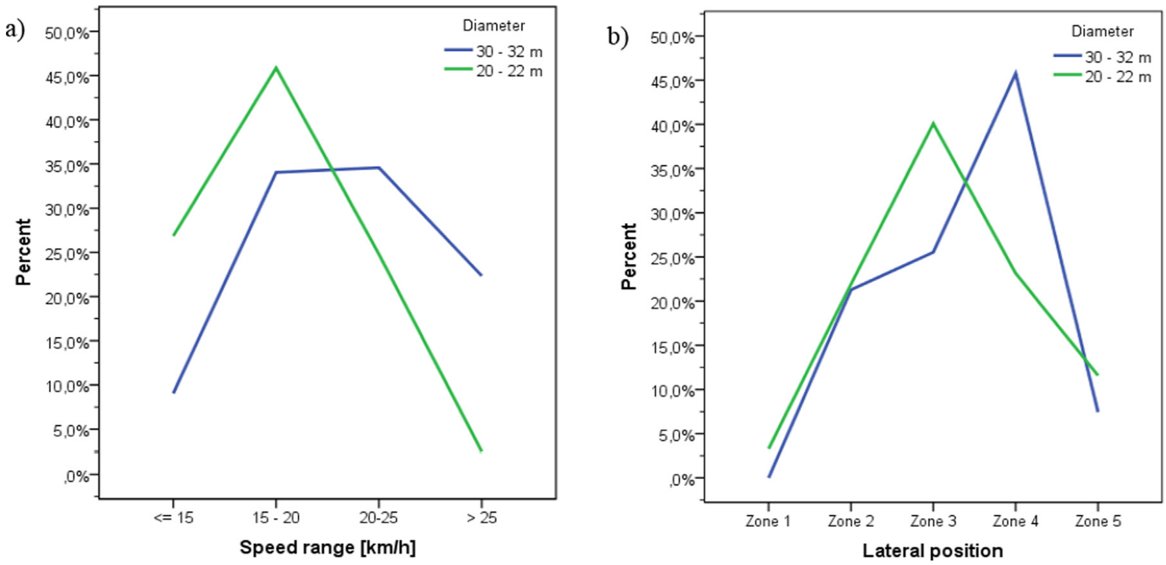

Fig. 4. a) Speed range of free-flow bicyclists for roundabouts with big diameter (30–32 m) and small diameter (20–22 m); b) Lateral position of free-flow bicyclists for roundabouts with big diameter (30–32 m) and small diameter (20–22 m).

about 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<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. $\leq$ *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. The normal shape of the statistics was tested before running the ANOVA. The Kolmogorov-Smirnov test was satisfied (p-value > 0.05) for both speed and lateral position datasets.

Table 5 shows the mean values of bicyclists' speed 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 Fig. 5-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.

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 Fig. 5-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.

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). Fig. 5-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 Fig. 5-a show that for both big and small diameters the mean speed of conditions 9 (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 Fig. 5-b show that for both big and small diameters also the mean normalized distance of conditions 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.

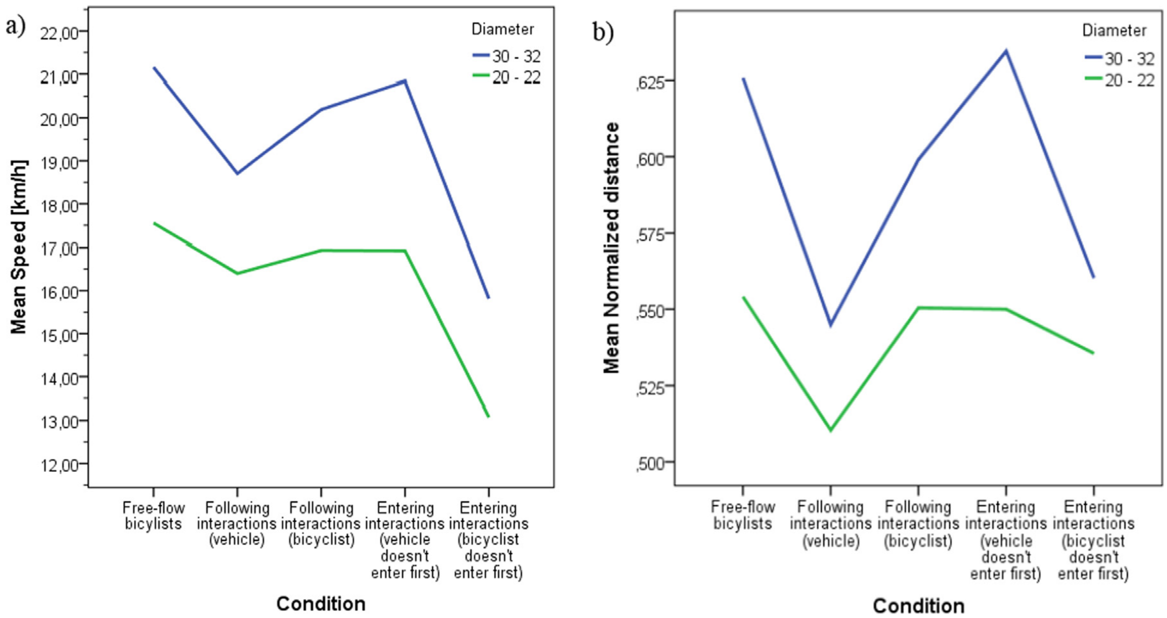

Fig. 5. a) Mean speed of bicyclists for each condition for roundabouts with big diameter (30–32 m) and small diameter (20–22 m); b) Mean normalized distance for each condition for roundabouts with big diameter (30–32 m) and small diameter (20–22 m).

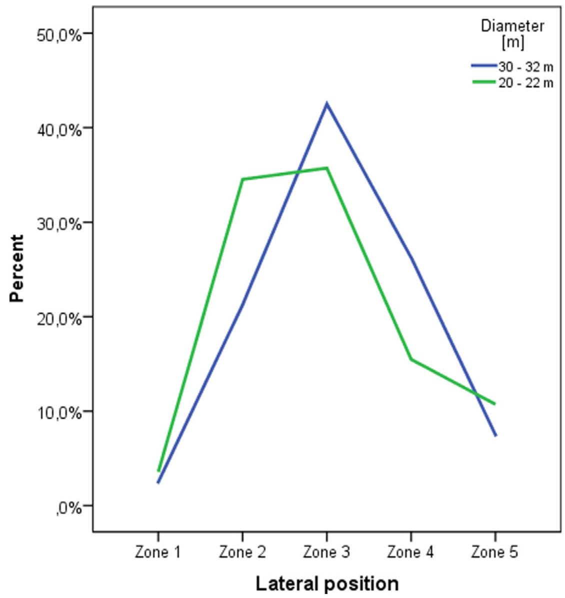

Fig. 6. Lateral position of bicyclists for interactions 2 (*following interactions – vehicle*) for roundabouts with big diameter (30–32 m) and small diameter (20–22 m).

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 Fig. 5-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). Fig. 6 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 Fig. 6 and Fig. 5-b it can be seen that for big diameter the majority of free-flow bicyclists rides in zone 4 (45.7%) while the majority of bicyclists who are followed by a vehicle rides in zone 3 (42.5%). In the same way, for small diameter the majority of free-flow bicyclists rides in 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). The mean speed of interactions 2 for both big and small diameter (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). 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).

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 Fig. 5-a). At the same time, mean nor-

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).

malized 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 Fig. 5-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.

3.2. Occurrence of close interactions

3.2.1. 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 h 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 h 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.

3.2.1.1. 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}<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}<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).

3.2.1.2. 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<1 s, corresponding to 6.96% of the total amount of interactions for big roundabouts. On the small roundabouts, 32 interactions have a PET<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).

3.2.1.3. 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 T2 min<1 s, corresponding to 7.50% of the total amount of interactions for big roundabouts. On the small roundabouts 38 interactions have a $T_{2\ min}$<1 s, corre-

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).

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).

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 = 1082 for the total).

sponding 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.

3.2.1.4. 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 h 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 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

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%).

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.

3.2.2. 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 h 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 Fig. 7. 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

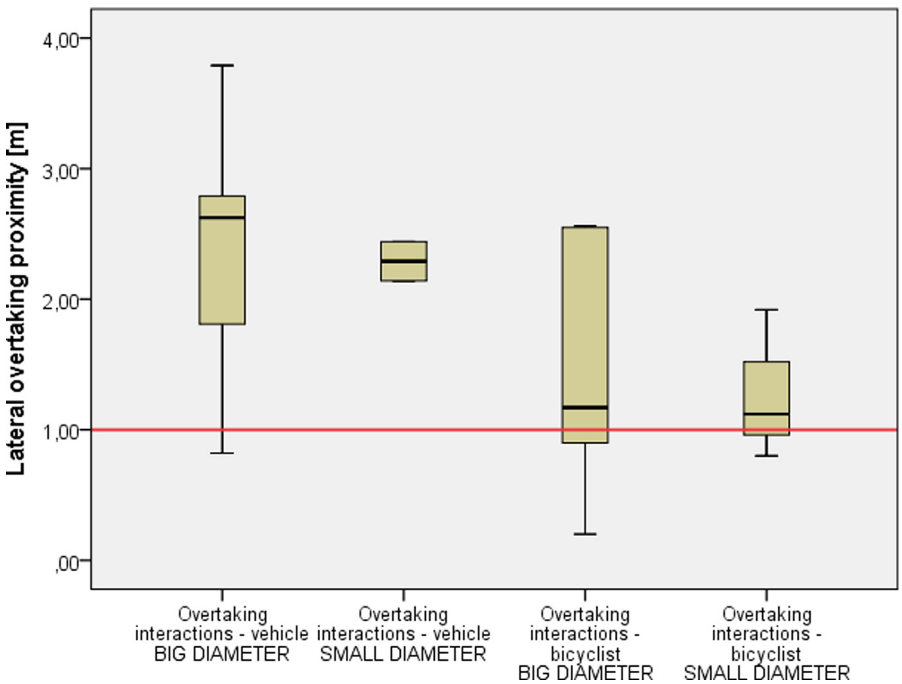

Fig. 7. Lateral overtaking proximity position of bicyclists for interactions 4 (*overtaking interactions – vehicle*) and for interactions 5 (*overtaking interactions – bicyclist*) for roundabouts with big diameter (30–32 m) and small diameter (20–22 m).

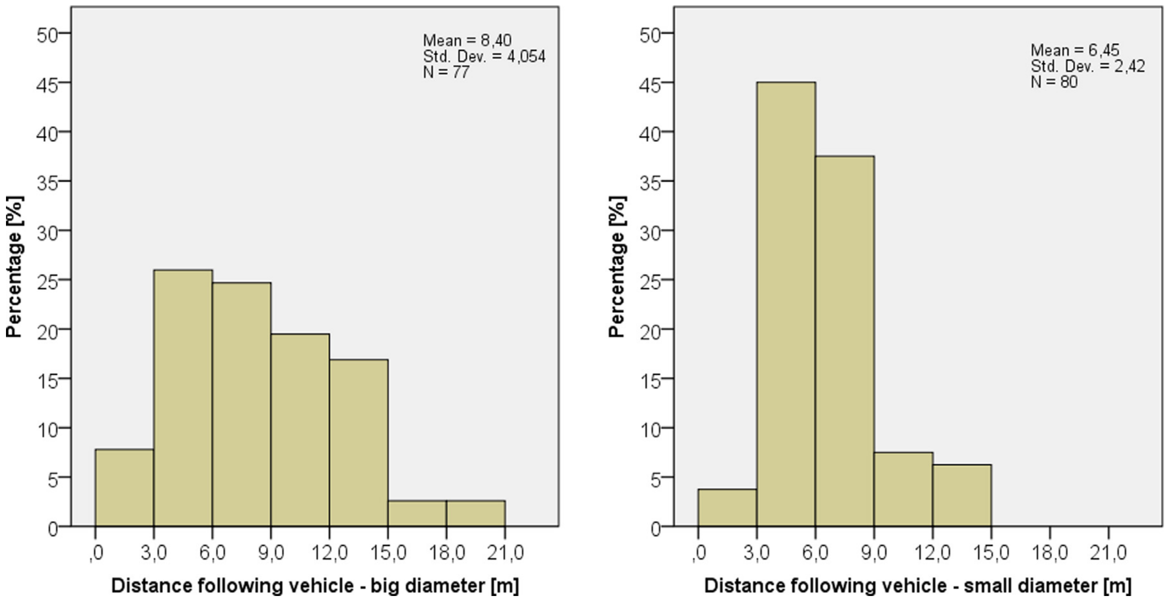

Fig. 8. Distribution of minimum distance headway values for following interactions – vehicle (condition 2). (Left: roundabouts with big diameter (30–32 m); right: small diameter (20–22 m).

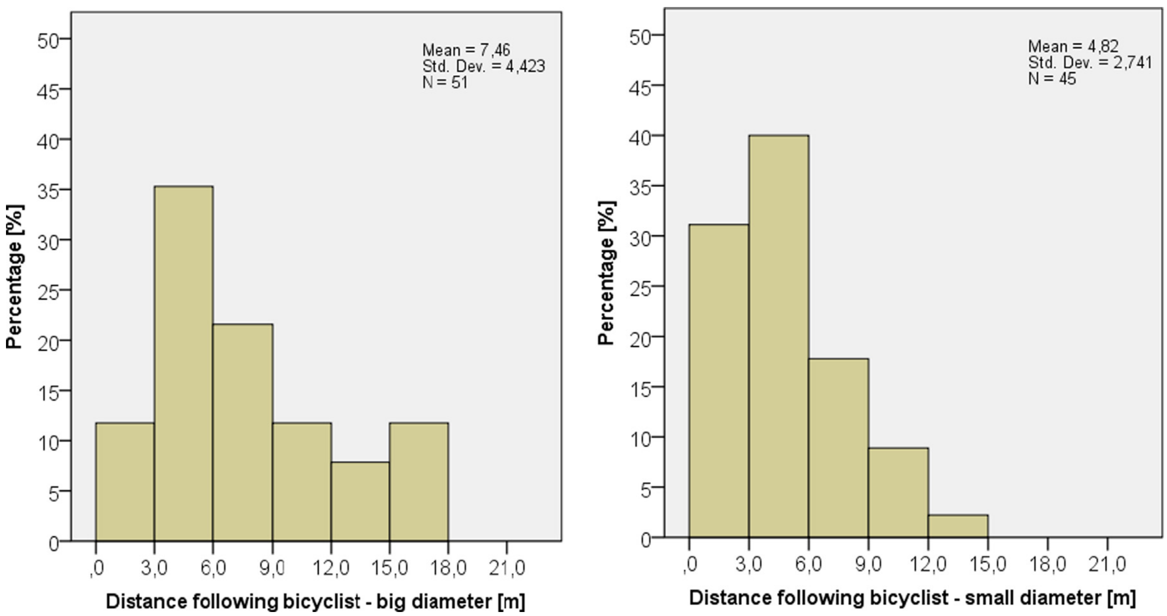

Fig. 9. Distribution of minimum distance headway values for following interactions – bicyclist (condition 3). (Left: roundabouts with big diameter (30–32 m); right: small diameter (20–22 m).

diameter (respectively 5 and 3 events observed). *Lateral overtaking proximity* values of *Overtaking interactions – vehicle* (condition 4) are lower than 1 m only for one event on roundabouts with big diameter. *Lateral overtaking proximity* values of *Overtaking interactions – bicyclist* (condition 5) are lower than 1 m for two events on roundabouts with big diameter and for one event on roundabouts with small diameter.

The box plots of Fig. 7 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<1 m is however not significantly different between both big and small roundabouts (the Fisher test gives p = 0.833 and p = 0.714).

3.2.3. Minimum distance headway

Fig. 8 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 h of video for each roundabout (Video Analysis 1). Fig. 9 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 h of video for each roundabout (Video Analysis 1). The *minimum distances headway* shown in Figs. 8 and 9 are obtained from the analysis of 16 h 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 m of Fig. 8 and Fig. 9 it can be seen that bicyclists who follow a vehicle seem to take smaller following distances than cars following a bicycle. Moreover, Fig. 9 shows that following distances for bicyclists who follow a vehicle are smaller at the small roundabouts (the *minimum distances headway* below 3 m are 12% for roundabouts with big diameter, while the *minimum distances headway* below 3 m 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<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).

4. Discussion

The analysis of behavioural aspects showed that bicyclists ride significantly faster on roundabouts with a 30 m diameter compared to roundabouts with a 20 m 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 a 30 m diameter and slower on roundabouts with a 20 m diameter. As for lateral position, the results showed that bicyclists ride closer to the central island on roundabouts with big diameter compared to roundabouts with small diameter 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 interaction type in which bicyclists changed their behaviour most strongly both in terms of speed and lateral position was found to be *following interactions – vehicle* (condition 2). 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. Possibly, bicyclists feel less safe while being followed by a vehicle and therefore tend to assume a position more towards the outside in order to facilitate being overtaken. This finding is in line with De Ceunynck et al. (De Ceunynck et al., 2017), who found that bicyclists also tend to ride closer to the edge of the road when followed by a bus. This could indicate a more general tendency (i.e. irrespective of context) of bicyclists to ride more closely to the edge of the road when in a mixed-traffic situation and having a motor vehicle behind them. This could be an interesting topic for further investigation.

Since bicyclists tend to assume a lateral position more towards the outside, the resulting trajectories on the circulatory roadway are likely longer and have a higher curvature compared to the trajectories of free-flow bicyclists. This results in a reduction of speed, which is confirmed by Table 5 and Fig. 5-a. 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 difference in mean speed between free-flow bicyclists and *Following interactions - vehicle* (condition 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 *Following interactions - vehicle* (condition 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 could suggest that bicyclists feel safer on roundabouts with small diameter and are therefore able to deal better with the presence of a following vehicle.

The results obtained of the behavioural analysis, could suggest that bicyclists feel safer on roundabouts with small diameter. This suggests the need of planning ad hoc solutions for bicyclists in case of roundabouts with big diameter. On the other hand, this could suggest bicyclists feel safer on roundabouts with small diameter even in mixed traffic conditions. However, the study does not make a direct comparison with possible alternatives for mixed traffic roundabouts, such as roundabouts with separate cycle paths or with marked cycle lanes adjacent to the circulation, and can therefore not provide a final recommendation on how these alternatives would perform compared to roundabouts with bicycle facilities.

As for the analysis of surrogate safety indicators, *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. 87 close interactions were identified, 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 situations involving a circulating vehicle and an entering bicycle are associated with the highest level of risk. This result is in line with previous studies showing that the crash frequency at roundabouts is higher when entering the roundabout (Mandavilli, McCartt, & Retting, 2009; Montella, 2011; Polders, Daniels, et al., 2015). Sakshaug et al. (2010) found that at mixed traffic roundabouts entering interactions between cyclists and vehicles represent the biggest problem. However, they found that the riskiest situation is motor vehicles entering the roundabout, i.e., vehicles not yielding to circulating cyclists.

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 than on roundabouts with small diameter. Also *Overtaking interactions – bicyclist* (condition 5) are 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 seem to take smaller following distances than cars following a bicycle.

The safety assessment carried out in this study is based on surrogate safety indicators and not on actual accidents. The use of surrogate safety indicators such as *Time to collision*, *Post-Encroachment-Time* and *T2-value* and the thresholds applied for assessing the safety of interactions could be debated. The validity of these indicators as surrogate measures of safety has not been sufficiently investigated in research. A low value for surrogate safety indicators does not automatically imply an unsafe interaction (although it could be uncomfortable for some of the road users). Moreover, most reported studies on traffic conflicts have focused only on interactions between motorised road users, while vulnerable road users (including bicyclists) have other capabilities to perform evasive actions (Laureshyn et al., 2017). It is therefore somewhat uncertain how strongly these indicators correlate with the prevalence of actual accidents, especially for vulnerable road users such as bicyclists. Nevertheless, previous research has shown strong correlations between surrogate safety indicators and traffic accidents (El-Basyouny & Sayed, 2013; Peesapati et al., 2013; Songchitruksa & Tarko, 2006). Earlier studies also attempted to validate surrogate safety indicators specifically for vulnerable road users and found a strong correlation between critical events and accidents (Lord, 1996; Sacchi, Sayed, & Deleur, 2013). Thus, the authors believe that it is reasonable to assume that the surrogate safety indicators used are sufficiently suitable to assess the safety of interactions between bicyclists and motorized vehicles at roundabouts.

A limitation to the presented study is that the observation period is relatively short for close interactions. 16 h of video were analysed for each roundabout to identify free-flow bicyclists, interactions and close interactions (Video Analysis 1) and 16 additional hours of video were analysed for each roundabout to identify additional close interactions (Video Analysis 2). This observation period ensured a sample size rather extensive as for free-flow bicyclists and interactions, but as for close interactions the sample size is rather small. While there are no reasons to believe that the observed roundabouts are atypical in any way, the generalizability of the results cannot be guaranteed. The aim was to include roundabouts that were as similar as possible according to the selection criteria. However, it is possible that minor design feature differences have influenced the results. Further studies may focus on overcoming the above-mentioned limitations. The sample size of close interactions could be increased and more locations could be observed in order to make the results more generalizable. The results of this study should be regarded as indicative of central issues worth studying further in relation to bicyclists' behaviour and safety at roundabouts.

5. Conclusions

The aim of this study was to increase knowledge about bicyclists' behaviour and safety at roundabouts without bicycle facilities with different diameter. The developed analysis allowed to evaluate if and how the diameter of the roundabout affects behavioural and surrogate safety indicators of bicyclists interacting with vehicles. Four urban roundabouts were observed, two with a diameter of approximately 30 m and two with a diameter of approximately 20 m.

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.

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. In conclusion, the analysis of the indicators to describe the closeness of interactions, 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.

CRediT authorship contribution statement

G. Pulvirenti: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing - original draft, Writing - review & editing. **T. De Ceunynck:** Conceptualization, Methodology, Validation, Investigation, Data curation, Writing - review & editing, Supervision. **S. Daniels:** Conceptualization, Resources, Writing - review & editing, Supervision, Project administration. **N. Distefano:** Conceptualization, Formal analysis, Writing - review & editing. **S. Leonardi:** Conceptualization, Resources, Writing - review & editing, Supervision, Project administration.

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