

# **Interaction between motor vehicles and bicycles at two-lane roundabouts: a driving volatility based analysis**

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## **Interaction between motor vehicles and bicycles at two-lane roundabouts: a driving volatility based analysis**

**Abstract:** Drivers' instantaneous decisions regarding speed and acceleration/deceleration, as well as the time rate of acceleration change (jerk) can result in a volatility driving behaviour with significant impact on cyclist safety. The contribution of this paper is the assessment of driving volatility in MV-bicycle interactions at two-lane roundabouts. Traffic flow and bicycle GPS data were collected from two two-lane roundabouts. Then, traffic, emissions and safety models were used to evaluate volatility impacts on safety, pollutant emissions and traffic performance. The findings showed jerk have impact on driving volatility between MVs and bicycles, regardless of roundabout design with a higher amplitude of variation for MVs. However, MVs had higher acceleration-deceleration variation than bicycles.

**Keywords:** Driving volatility; Cyclists; Roundabout; Safety; Emissions.

## 1. Introduction and objectives

Policy revisions, infrastructure improvements, and individual benefits of bicycles along with positive effects on air pollutants and environmental issues have led to the increase of cycling rate at urban areas (Twaddle, Schendzielorz, & Fakler, 2014; Silvano, Ma, & Koutsopoulos, 2015). The impact of modal shift from car to cycling and public transportation can result in relevant health benefits, especially those regarding the increase of physical activity, and secondary in the reduction of air pollution impacts (e.g. particulate matter  $< 2.5\mu\text{m}$ ) in population (Rojas-Rueda, De Nazelle, Teixidó, & Nieuwenhuijsen, 2012). According to the European Cyclists' Federation (EFC), the economic benefits of cycling regarding carbon dioxide ( $\text{CO}_2$ ) emissions, air pollution and noise were estimated by 3bn € in the 28 European-countries (EU28) (Ferguson et al., 2018).

One concern that arises from bicycle use is the risk-exposure for cyclists (Fernandez-Heredia, Monzón, & Jara-Díaz, 2014). In 2016, about 2,000 cyclists were killed in road traffic accidents in EU28, constituting 8% of all road accident fatalities. In 2016, 51 cyclists died after crashing at roundabouts in EU28 (approximately 2.5% of the cyclist-intersection fatalities) (EC, 2018).

The benefits of roundabouts are well-reported: lower number of conflict points than the traditional stop-controlled and signalized intersections, low approaching and circulating speeds, and effectiveness in reducing unnecessary driving volatility by reduction in motor vehicle (MV) stops (Rodegerdts et al., 2007, 2010; Jensen, 2017). Nevertheless, cyclists at roundabouts constitute a specific problem for safety at roundabouts (Rodegerdts et al., 2010; Brilon, 2016; Ferguson et al., 2018).

The bicycle facility and infrastructures (Koorey & Parsons, 2016; Daniels, Brijs, Nuyts, & Wets, 2009), speed limits (Silvano et al., 2015), design (Jensen, 2017), and traffic volumes (Rodegerdts et al., 2010) are pointed out as factors that can influence bicycle safety at roundabouts. Speed is a fundamental risk factor in cyclist safety (Silvano et al., 2015), especially at roundabout entry and exit legs while the MV and bicycle are circulating near each other. Speed also plays an important role in the definition of driving style based on the speed limits and driver's decision in choosing the proper speed (Liu, Khattak, & Wang, 2017). The prior research showed a positive correlation between the frequency of driving speed exceeding the speed limit and the number of road traffic crashes (af Wåhlberg, 2006). Moreover, it can result in the increasing volatility driving behaviour of MV driver during MV-bicycle interaction. In this situation, drivers might have to rapidly adapt by changing speed, acceleration/deceleration variation or vehicular jerking (which is defined by the change in the rate of acceleration or deceleration) to avoid the collision. The instantaneous yielding behaviours of drivers and cyclists, such as rapidly braking or acceleration can dictate safety concerns.

Drivers' instantaneous decisions to change speed and subsequently acceleration/deceleration (aggressive driving behaviours) affect energy consumption significantly, emissions, and safety outcomes (Liu et al., 2017; Wang, Khattak, Liu, Masghati-

Amoli, & Son, 2015; Park, Yun, & Ahn, 2009). According to a recent study by Liu et al., (2017), volatility driving is associated with speed and acceleration variation or vehicular jerking by drivers, which in turn increases the fuel consumption and risks of crash occurrence. Vehicular jerk is a change rate of vehicle acceleration with respect to time as a result of aggressive driving, fast shifting gears, and hard braking. Mathematically, jerk is defined as the first derivative of acceleration/deceleration (second derivative of speed) with positive or negative value.

Sudden or rapid variation in speed and subsequently in acceleration/deceleration means changing driving behaviour in a very short period that is not enough to driver and other road users react properly (Feng et al., 2017). Speed variation and subsequently acceleration/deceleration variation are the main factors of driving volatility for both bicycle and MV. Wang, Zhou, Quddus, & Fan (2018) showed that a high volume of speed variation was associated with increased crash frequency. However, the correlation between volatility driving and crash risk has been found in previous studies (Zaki, Sayed, & Shaaban, 2014; Feng et al., 2017).

Kamrani, Arvin, & Khattak (2018a) introduced a new way to measure the vehicle volatility for alternative fuel vehicles, based on time-varying stochastic volatility. The research was not only based on driver styles (vehicular speed, acceleration, jerk) but also different types of vehicles (hybrid, plug-in, hybrid electric, CNG, and electric vehicles). The findings showed that these vehicles are less volatile compared to conventional vehicles.

The cyclist impedance effect increases under high bicycle volumes thereby affecting intersection-specific capacity and increasing vehicular emissions. Research around this topic is widespread [about safety: (Jensen, 2017; Brilon, 2016; Daniels et al., 2008, 2009), about safety-traffic performance (Rodegerdts et al., 2007; Silvano et al., 2015), and about safety-emissions-traffic performance (Roach, 2015)], but little was discussed about MV-bicycle interaction at roundabouts or driving volatility. The few studies around this topic analysed the impacts of driver biometrics data (Kamrani, Khattak, & Li, 2018b), infrastructure (Kamrani et al., 2018b) and alternative fuel vehicles (Kamrani et al., 2018a) on driving volatility. This happens not only for MVs but also between MVs and bicycles. Several studies have been focused on the impact of the roundabout on cyclist safety (Rodegerdts et al., 2010; Jensen, 2017; Koorey & Parsons, 2016; Daniels et al., 2008, 2009), but they did not include the effect of driving volatility and the role of MV-bicycle interaction.

Thus, the motivation of this research is to assess the impact of driving volatility of cyclists and MVs on traffic performance, vehicular emissions, and cyclist safety. Speeds and acceleration variation (jerk) were analysed in the circulating area of the roundabout to assess the influence on: 1) drivers' volatility interacting with cyclists; 2) emissions and 3) corresponding roundabout-specific traffic performance and safety outcomes. This research investigates these concerns at real-world two-lane roundabouts without dedicated bicycle lanes in urban areas that experience different designs, and traffic and bicycle demand. The novelty of this research is assessment of the impacts of cyclists and MVs driving volatility [not only MV like in previous research (Kamrani et al., 2018a, Liu et al., 2017; Wang et al., 2015)] on traffic performance, safety and emissions at roundabouts on an integrated way. The specific objectives of this paper is threefold:

- To identify the main factors of driving volatility as a result of MV-bicycle interactions at two-lane roundabouts;
- To investigate the impact of driving volatility on CO<sub>2</sub>, carbon monoxide (CO), hydrocarbon (HC) and nitrogen oxides (NO<sub>x</sub>) emissions per unit distance;
- To evaluate the impact of MV-bicycle interaction on traffic performance and cyclist safety.

## 2. Methodology

The main idea of the methodology was to combine field measurements and microsimulation tools to characterize MVs and cyclists interactions at two-lane roundabouts. First, data were collected from studied locations, then the jerk, acceleration and speed were analysed for MVs and bicycles. Along these, the Vehicle Specific Power (VSP) methodology were used to estimate CO<sub>2</sub>, NO<sub>x</sub>, CO, and HC emissions generated by MVs. In turn, simulation uses a microscopic traffic model paired with safety model (Surrogate Safety Assessment Model – SSAM) to examine MV-bicycle interactions at roundabouts and to estimate conflicts resulting from MV-to-MV and MV-to-bicycle interactions and the following safety indicators: Time-to-Collision (TTC), Post-Encroachment Time (PET), Deceleration Rate (DR), maximum speed (MaxS) and maximum relative speed difference (DeltaS) (Gettman, Pu, Sayed, & Shelby, 2008). Fig. 1 illustrates the conceptual framework of the research.

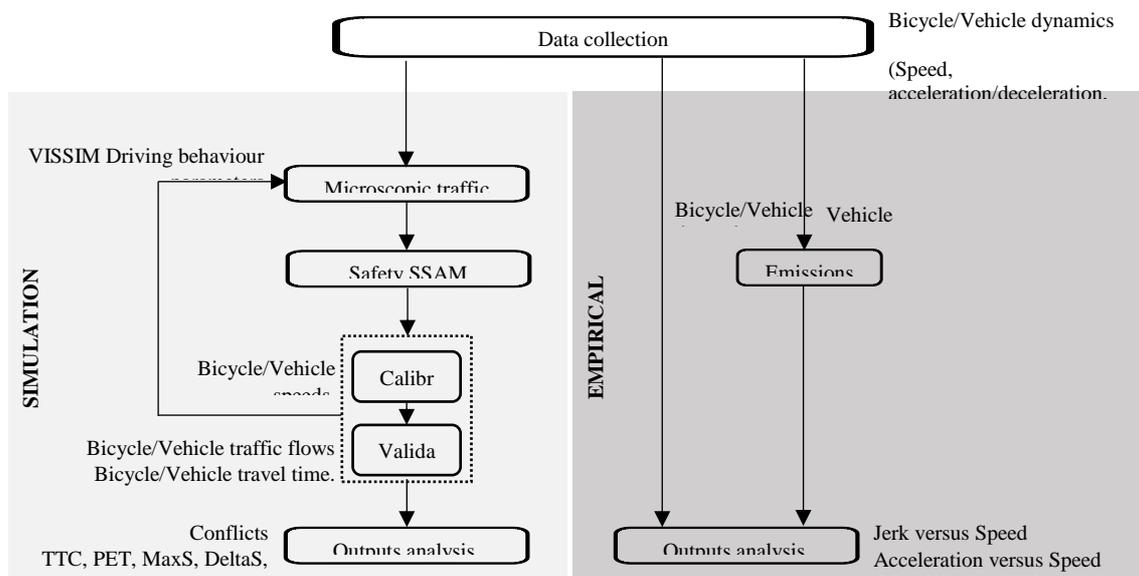


Fig. 1. Methodological framework.

### 2.1. Traffic modelling

VISSIM (PTV, 2016) offers good support for modelling driving behaviour parameters (e.g., gap acceptance and lateral movements) in roundabouts (Li, DeAmico, Chitturi, Bill, & Noyce, 2013) and it is also able of reproducing the complex nature of interactions between vehicles and bicycles at roundabouts (Bergman, Olstam, & Allström, 2011; Abhigna, Kondreddy, & Shankar, 2016). The study of bicycle movements and behaviour parameters are highly important for bicycle simulation and calibration procedure (Ma & Luo, 2016) and for calibration process as well.

## 2.2. Emission estimation

Emission estimation is based on the concept of Vehicle Specific Power. The scope of analysis is focused on vehicular emissions for global (CO<sub>2</sub>) and local (NO<sub>x</sub>, CO, and HC) pollutants. VSP is computed from a second-by-second speed profile based on parameter values for a typical Light-Duty Vehicle (LDV) (Frey et al., 2002). VSP is associated with any speed trajectory and it provides reliable vehicular emission estimates at roundabouts since it accounts for changes in vehicle dynamic in the approach, circulating and exit areas (Coelho, Farias, & Roupail, 2006; Salamati et al., 2013). Equation 1 provides the generic VSP equation from a typical LDV (Frey et al., 2002):

$$\text{VSP} = v \cdot [1.1 a + 9.81 (a \cdot \tan(\sin(\text{grade}))) + 0.123] + 0.000302v^3 \quad (1)$$

Where: VSP – vehicle specific power (kW/metric ton); v – Instantaneous speed on a second-by-second basis (m/s); a – acceleration-deceleration rate on a second-by-second basis (m/s<sup>2</sup>); grade – road grade (%).

Each VSP bin refers to one of 14 modes. Each mode is defined by a range of VSP values that are associated with an emission factor for CO<sub>2</sub>, CO, NO<sub>x</sub> and HC concerning the Gasoline Passenger Vehicles (GPV) (Anya, Roupail, Frey, & Liu, 2013), Diesel Passenger Vehicles (DPV) and Light Duty Diesel Trucks (LDDT) (Coelho, Frey, Roupail, Zhai, & Pelkmans, 2009).

## 2.2. Safety model

SSAM (Gettman et al., 2008) was selected to simulate traffic conflicts between MVs, and between MV and bicycles. This post-processing tool automates traffic conflict analysis using vehicle and bicycle trajectories from a microscopic traffic model as VISSIM. Afterwards, it records surrogate measures of road safety and determines whether an interaction between MV-to-MV and MV-to-bicycle satisfies the condition to be considered a conflict (Gettman et al., 2008).

A good body of research have identified some limitations of SSAM tool, namely: i) inability of evaluating complex real-world driving behaviors, for instance interactions that results in side-wipe conflicts; ii) it only provides a graphical user interface which became automatic calibration procedure impracticable (time consuming); and iii) unviability of SSAM to determine the probability of each estimated conflict turning into a crash (Gettman et al., 2008; Huang, Liu, Yu, & Wang, 2013; Fernandes, Sousa, Macedo, & Coelho, 2019).

Despite these drawbacks, some authors have found reasonable relationships between SSAM conflicts and crashes in roundabout layouts, thus showing to be a good approach to assess the relative safety of different single- and two-lane roundabout layouts (Al-Ghandour, Schroeder, Williams, & Rasdorf, 2011; Vasconcelos, Neto, Seco, & Silva 2014; Giuffrè et al., 2019).

TTC is used as a threshold to define whether a MV-MV and MV-bicycle interaction is a conflict. This surrogate measure is defined as the minimum time-to-collision of two MV or MV-

bicycle on a collision route. Minimum TTC and PET are used to assess the severity of a given conflict event while DR, MaxS and DeltaS are indicators of the potential crash severity (Gettman et al., 2008).

### 2.3. Site selection and studied locations

To evaluate the impacts of driving volatility between cyclists and MVs on traffic performance, emissions, and cyclist safety, two conventional two-lane roundabouts in the urban area of Aveiro (Portugal) were selected. Roundabout R1 is in the city centre with an average of 65 bicycles per hour (bph) (Fig. 2a). There are positive slopes up to 3.5% between some roundabout legs and central island that creates some visibility problems for both approaching vehicles and cyclists. Roundabout R2 is an interchange roundabout with six legs. The number of cyclists is 12 bph (Fig. 2b).



Fig. 2. Layout of the case studies with the identification of legs and videotaping location. [Source: Google Maps]

R1 and R2 were chosen due to the fact that they have the same number of circulating lanes and absence of dedicated bicycle lanes, but variations in bicycle demands, design, and capacity.

Crash data involving motor vehicles and cyclists at R1 and R2 were gathered for 3-years' time period between 2015 and 2017 (ANSR, 2019). The database covered a total of 11 and 2 crash observations at R1 and R2, respectively, and with the following distribution of mode of transportation: R1 – 7 two-vehicle crashes (motor only); R1 – 4 crashes involving a motor vehicle and a cyclist; R2 – one single-vehicle crash; R2 – one crash involving a motor vehicle and a pedestrian.

The cameras were set up in the field to adequately cover the entire roundabout movements. This data collection was carried out for both morning and afternoon peak periods (8-10 AM and 5-7 PM), under dry weather conditions, for two days. Complementary, GPS data can help to capture drivers' volatility behaviours (Wang et al., 2015) interacting with bicycles. Thus, a test-equipped MV and a bicycle with GPS collected second-by-second speed, distance travelled, and acceleration-deceleration rates. Total data included more than 6 000 seconds of vehicle and bicycle GPS data. In order to assure variability in field tests, three different test-drivers (two male

and one female) and two different test-cyclists participated in both vehicle and bicycle GPS data collection, respectively.

The details of MV-bicycle interactions were recorded by co-pilot on the provided data sheets during test periods. Time, location and type of interaction defined by Sakshaug, Laureshyn, Svensson, & Hydén (2010) were recorded during GPS data collection. The locations of interactions were categorized as entry lane, exit lane, parallel movement, and circulating. Vehicular jerk values were collected as the second derivative of speed (the derivative of acceleration) based on the provided data from GPS. Other variables, such as enter and exit traffic volumes, queue lengths and conflicting traffic flow were extracted from video data. The Level-Of-Service criteria (LOS) and queue distance by lane were collected from traffic data measurements using the Highway Capacity Manual methodology (TRB, 2016). The key characteristics of case studies are summarized in Table 1.

Table 1. Summary results of baseline and alternative Scenario (I)

Roundabout	Circulating Width [m]	Inscribed Circle Diameter [m]	Leg	LOS	Queue [m]	Entry traffic [vph]	Exit traffic [vph]	Entry bicycles [bph]	Exit bicycles [bph]	Intersection LOS
R1 (Aveiro city centre)	8	50/45 <sup>a</sup>	L1	C	98	526	382	26	29	C
			L2	C	48	232	159	18	14	
			L3	D	114	550	475	22	25	
			L4	B	41	327	433	20	11	
R2 (Shopping centre)	8	55	L1	F	135	381	756	3	0	D
			L2	C	86	581	492	10	10	
			L3	D	80	278	410	9	7	
			L4	C	205	628	268	2	0	
			L5	D	118	442	373	4	9	
			L6	B	73	677	537	11	16	

<sup>a</sup>Oval roundabout that has two values for Central Island

Fig. 3 a-b shows all combinations of bicycle speed profiles with none, one and multiple stops that were extracted from GPS data at R1 (L3 → L1) and R2 (L6 → L2). For this analysis, an average roundabout influence area of 200 m was considered in the simulation. This is defined as the sum of the deceleration distance that a vehicle travels from cruise speed as it approaches the roundabout and enters the circulating lane and acceleration distance as it leaves the roundabout up to the point it regains the cruise speed (Fernandes et al., 2016). In certain occasions due to the pedestrian crossing (Bergman et al., 2011) and congested traffic at R1 and R2, cyclists stops before and after circulatory carriage. In summary, cyclist speed profiles followed the same pattern as MV did (Salamati et al., 2013) with deceleration from upstream to circulating area of roundabout followed by an acceleration while the cyclist is leaving the roundabout.

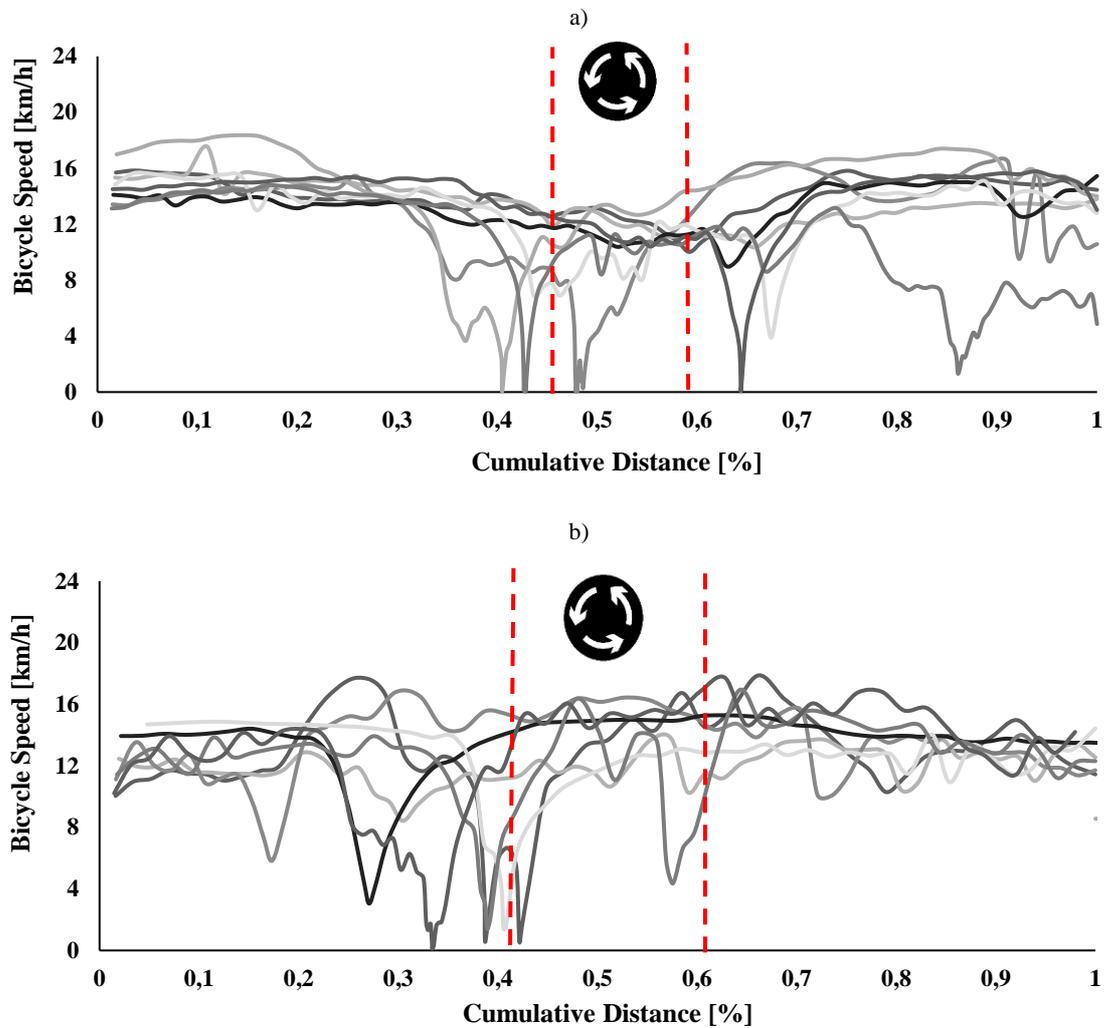


Fig. 3. Representative speed profiles for a bicycle: a) R1 (L3 → L1) and b) R2 (L6 → L2).

### 2.3.1. Traffic Model Coding, and Calibration and Validation procedures

The simulation was separately done for each roundabout between 6:20 PM and 7:30 PM. A “warm-up” was included during the first 10-minutes to load the road network with corresponding flows. The treatment of the yield areas took into account local-specific headway and critical gaps. Regarding MVs and bicycles movement in the shared road without any physical barrier, some parameters, such as overtaking opportunities and lateral lane position for both cyclists and drivers were considered (besides speed distribution, road width, and number of lanes or volumes).

VISSIM traffic model was initially calibrated to reproduce traffic and bicycle flows R1 and R2 by coded link. Thus, a sensitivity analysis of VISSIM driving behaviour parameters (car-following, gap-acceptance, and lane change) was carried out to assess their impacts on traffic and bicycle volumes (Fernandes et al., 2016). This comparison was done using 10 different runs (Hale, 1997). The modified chi-squared statistics Geoffrey E. Havers (GEH), which incorporates both absolute and relative differences in the comparison of estimated and observed volumes, was used as the calibration criteria (Dowling, Skabardonis, & Alexiadis, 2004). In this research, the model calibration compared MV and bicycle flows and travel time between estimated and observed data. The calibration criterion was that GEH should be less than 4 at least 85% of the coded links (Dowling et al., 2004).

SSAM was also calibrated by comparing estimated and observed conflicts between MVs and bicycles. Using videotaping, the research team obtained the traffic conflicts (Huang et al. 2013) in both R1 and R2 in 15-min intervals. To be consistent with the conflict types computed by SSAM, the observed conflicts were classified into three types: a) Rear-end conflicts; b) Lane-change conflicts; and c) Crossing conflicts. After that, SSAM conflicts for both sites were computed for a TTC range interval from 1.0 to 2.0 seconds with 0.1-increment.  $TTC = 1.5$  was adopted for urban areas to define a conflict, as suggested by Huang et al. (2013). Then the obtained number of MVs-bicycle conflicts were compared against observed data for each TTC value to find the optimum TTC value for each study case.

There are virtual crashes, i.e. conflicts with  $TTC = 0$  seconds that are reported by SSAM. These phenomenon result from abrupt lane-change behavior while vehicles are entering, circulating or leaving roundabouts or failing to yield to conflicting traffic at low gaps. Therefore, the research team filtered out  $TTC = 0$  after calibration, either by correcting coded links or at adjusting driving behavior parameters, until virtual crashes represented less than 10% of total conflicts (Fernandes et al., 2019).

Model validation compared observed and simulated bicycle and MV speeds by coded link using the optimal VISSIM calibrated parameters with 10 random seed runs.

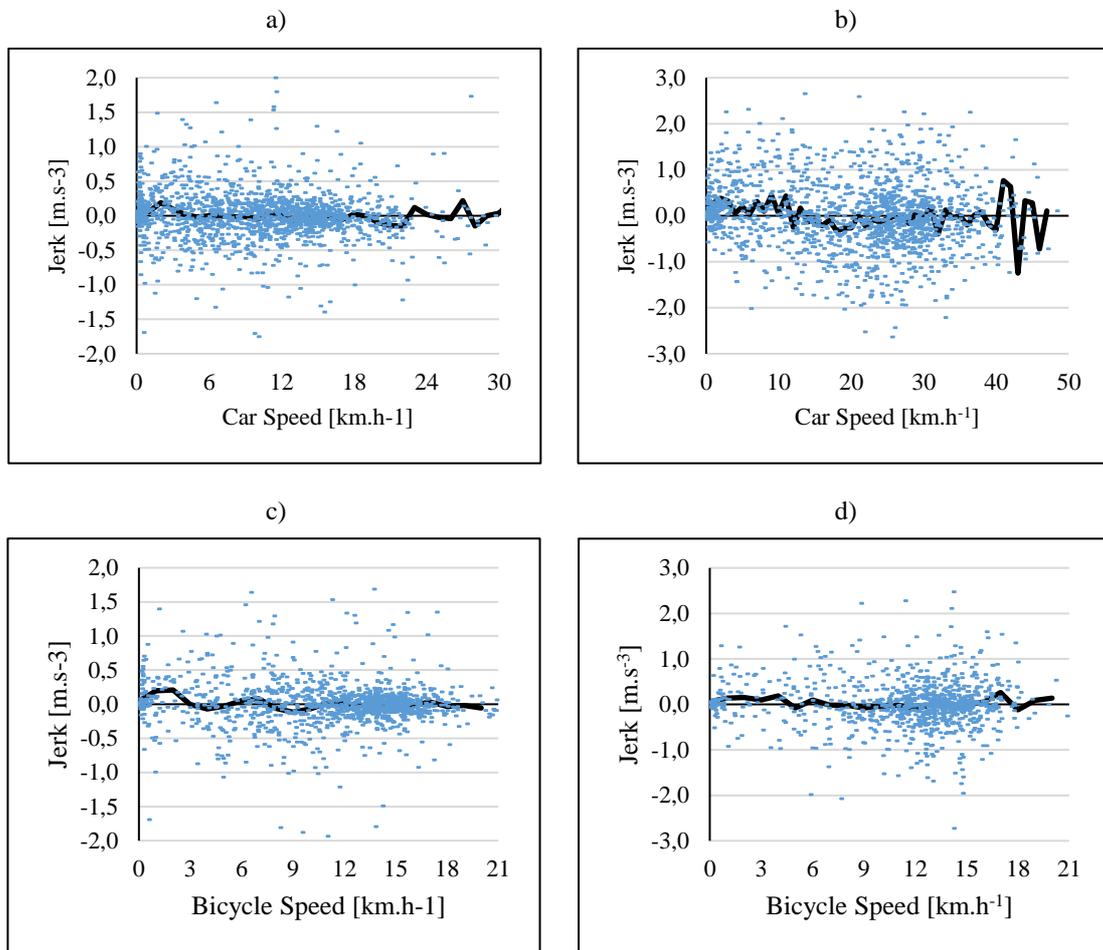
### **3. Results**

In this section, the main results from the field measurements are analysed (Section 3.1) followed by the simulation calibration and validation (Section 3.2) and safety analysis (Section 3.3).

#### ***3.1. Field Measurements***

##### ***3.1.1. Jerk versus Speed***

Jerk values were plotted against speed for both motor vehicles and bicycles, as depicted in Figure 4 (a-d). Each value of jerk represents the difference between acceleration is the second of travel  $i+1$  and acceleration is the second of travel  $i$ . The jerk evolution for bicycle and MV was identical within R1 and R2, but R2 yielded in sharp jerk values for these modes. Despite similar in the same roundabout, jerk variation was notably higher for MVs than for bicycles (Fig. 4a-b), especially in the R2. This occurred for three main reasons: 1) low cycling activity; 2) vehicles drove at high approach, circulating and exit speeds (MV average measured speed was 20 km/h and 11 km/h in R2 and R1, respectively); and 3) drivers had sharp acceleration or deceleration to avoid a crash with bicycles.

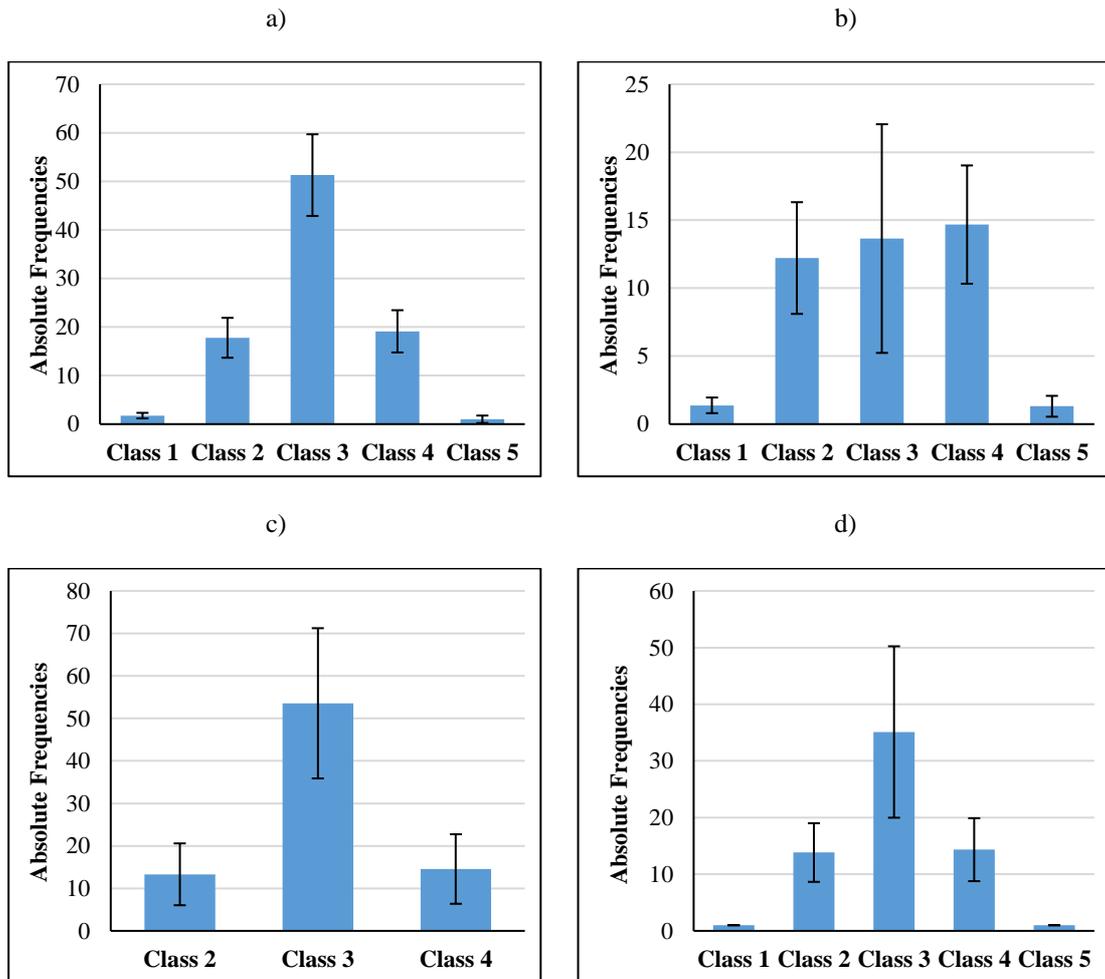


Legend: Dash line is the average jerk value for a speed bin in 1 km/h interval

Fig. 4. Traffic performance: a) Speed-based volatility of MV at R1; b) Speed-based volatility of MV at R2; c) Speed-based volatility of bicycle at R1; d) Speed-based volatility of bicycle at R2.

### 3.1.2. Acceleration versus Speed

Figure 5a-d represents the time spent in each acceleration class, ranging from high decelerations (class 1) to high accelerations (class 5), according to the previous work conducted by Fernandes, Salamati, Roupail, & Coelho (2015) in two-lane roundabouts. It can be observed that vehicles spent 56% of time in acceleration class 3 ( $-0.2 \text{ m.s}^{-2} < a < 0.2 \text{ m.s}^{-2}$ ), and 41% in acceleration classes 2 ( $-2 \text{ m.s}^{-2} < a < 0.2 \text{ m.s}^{-2}$ ) or 4 ( $0.2 \text{ m.s}^{-2} < a < 2 \text{ m.s}^{-2}$ ). For R2, the percentage in class 3 dropped to 31% while class 2 and 4 contributed together almost 70%. A close look to Figure 7 also confirmed that cyclists had sharper accelerations-decelerations in R2 than R1. For instance, they spent 65% and 29% of time in acceleration class 1, 2, 4 and 5 in R2 and R1, respectively. The size of error bars (standard deviation) values seems to confirm higher variation of values in R2. The Kolmogorov-Sminorv test (two-sample K-S test) confirmed that MVs from R1 and R2 and bicycles from R1 and R2 came from the same distribution at 95% confidence level; D-value were 0.15 (D-critical = 0.29) and 0.08 (D-critical = 0.23) for MVs and bicycles, respectively.



Legend: Class 1 [ $a < -2 \text{ m.s}^{-2}$ ]; Class 2 [ $-2 \text{ m.s}^{-2} < a < -0.2 \text{ m.s}^{-2}$ ] Class 3 [ $-0.2 \text{ m.s}^{-2} < a < 0.2 \text{ m.s}^{-2}$ ] Class 4 [ $0.2 \text{ m.s}^{-2} < a < 2 \text{ m.s}^{-2}$ ]; Class 5 [ $a > 2 \text{ m.s}^{-2}$ ]

Fig. 5. MV Acceleration class by mode and case study: a) MV – R1; b) MV – R2; c) Bicycle – R1; d) Bicycle – R2.

In Figure 6, all second-by-second MV and bicycle acceleration were plotted against MV and bicycle speed for all trips. R2 covered a wide band of acceleration-deceleration and speed combinations for MV compared to R1. This happened because MVs had sharp acceleration and deceleration rates in R2 compared to R1 as result of some cautions driving (perhaps due to inefficient visibility) on this latter roundabout. Although the range of bicycle values was identical in R2 and R1 (0 to 21 km/h), there was a higher range of variation of acceleration/deceleration at low speed values ( $< 10 \text{ km/h}$ ) in the second case study. The field data showed higher MV acceleration-deceleration variation than bicycles did, which is in accordance with previous studies in roundabouts (Silvano et al., 2015).

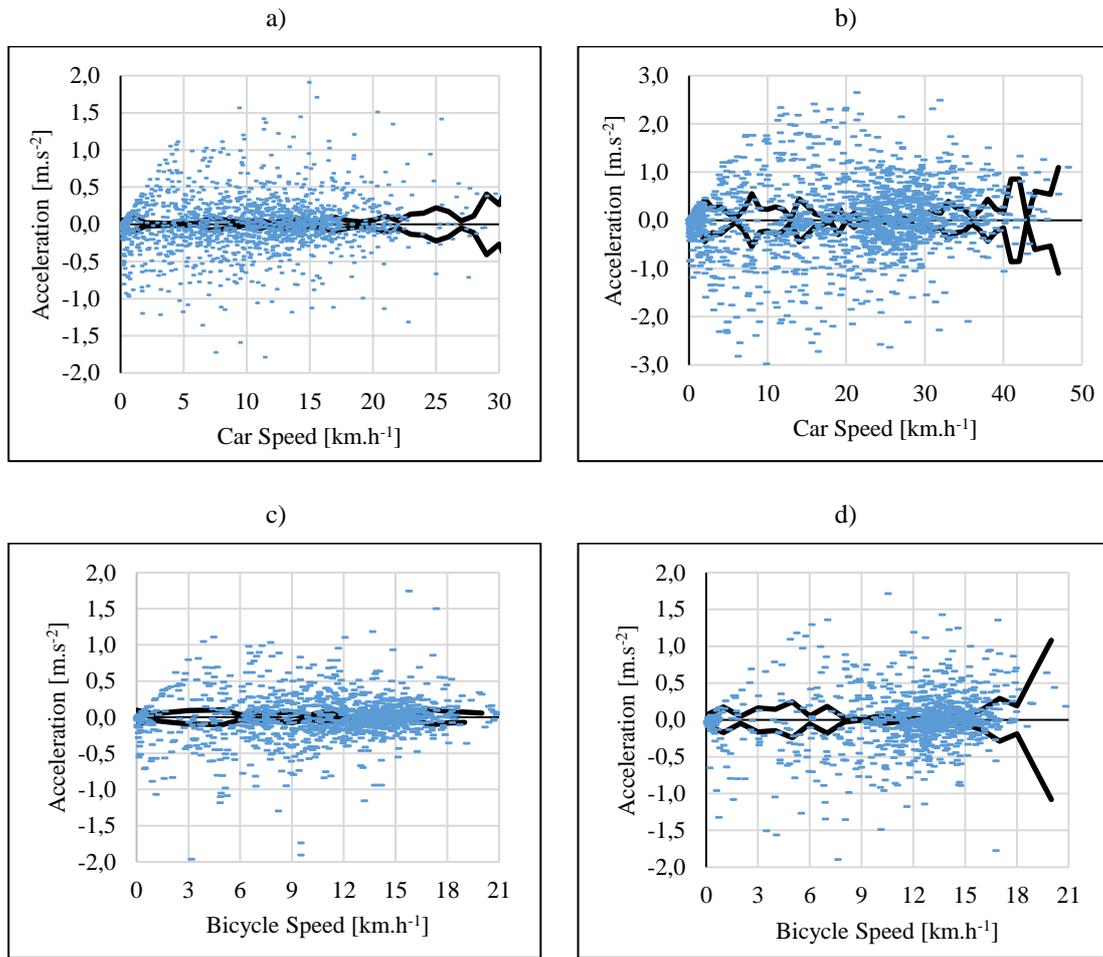


Fig. 6. Acceleration/deceleration versus speed by mode and roundabout: a) MV – R1; b) MV – R2; c) Bicycle – R1; d) Bicycle – R2.

### 3.1.3. Driving volatility impact on emissions

A relationship between driving volatility and pollutant emissions was conducted (see Fig 7 a-b). Results confirmed that, on average, MVs spent more time in idling (VSP mode 3) in R1 (~36%) than R2 (~19%). However, this latter layout recorded VSP modes higher than 8. To complement the analysis, the Kolmogorov-Sminorv test (two-sample K-S test) was used to assess if the VSP modal distribution between roundabout differed significantly on all routes performed at 95% confidence level. It was found that  $D$ -value was 0.23 ( $D$ -critical = 0.24), thereby suggesting a same distribution of R1 and R2 modes distribution.

The comparison of emission for both layouts dictated higher emission per unit distance for R2; CO<sub>2</sub>, CO, NO<sub>x</sub>, and HC were, respectively, 297 (g/km), 436 (mg/km), 583 (g/km), and 19 (mg/km). Concerning the R1, CO<sub>2</sub>, CO, NO<sub>x</sub>, and HC were, respectively, 272 (g/km), 370 (mg/km), 517 (g/km), and 20 (mg/km).

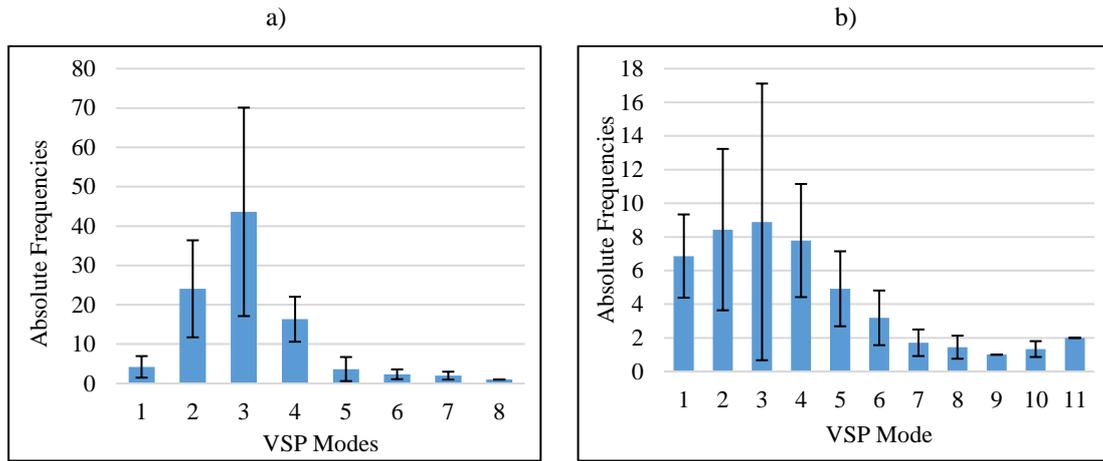


Fig. 7. VSP modes distributions (with standard deviation) by roundabout a) R1; and b) R2.

### 3.2. Calibration and validation

The calibration and validation of modelling platform was performed on a link-basis. The summary of calibration for the traffic model with adjusted parameters at R1 and R2 (considering the same driving parameters) is presented in Table 2. A good fit between observed and estimated data was obtained using a linear regression analysis with the values of R-squared ( $R^2$ ) higher than 0.9. With respect to the safety model, SSAM conflicts were computed using the threshold TTC values of 1.5 s and 1.6 s at R1 and R2, respectively ( $R^2 = 0.76$  and  $R^2 = 0.72$  at R1 and R2 respectively). Those TTC thresholds yielded the lowest Mean Absolute Percent Errors (MAPE) values between estimated and observed conflicts (15%-R1; 10%-R2).

Regarding the model validation, the average speed of bicycle and MV were conducted using 100 floating bicycles and the MVs (Dowling et al., 2004). The differences between observed and estimated average speeds at a 95% confidence interval were not statistically significant: 1) Speed (R1-MV) (p-value = 0.75); 2) Speed (R2-MV) (p-value = 0.58); 3) Speed (R1-Bicycle) (p-value = 0.25); and 4) Speed (R2-Bicycle) (p-value = 0.18).

Crash data showed low frequency of annual crashes in both roundabouts data showed low frequency of crashes in both roundabouts, especially those involving motor vehicles and cyclists. Therefore, the validation of the modeling platform did not include any validation of SSAM conflicts. For purpose of analysis, traffic conflicts were computed using the default TTC value of 1.5 s, as suggested by F. Huang et al. (2013) in urban areas. The VISSIM calibrated parameters in Table 2 were further applied to assess safety on the studied locations.

Table 2. Summary of calibration for the traffic model with adjusted parameters at R1 and R2.

Parameter	Value	GEH	R <sup>2</sup>	MAPE
Average standstill distance (m)	1	< 4 for 95% of the links	Flows (R1-MV) <b>(0.97)</b>	Flows (R1-MV) <b>(2.1%)</b>
Additive part of safety distance	1			
Multiple part of safety distance	1.10		Flows (R2-MV) <b>(0.99)</b>	Flows (R2-MV) <b>(0.5%)</b>
Visibility	95			
Front Gap (s)	0.5		Flows (R1-Bicycle) <b>(0.95)</b>	Flows (R1-Bicycle) <b>(3.2%)</b>
Rear Gap (s)	0.5			
Safety Distance	1		Flows (R2-Bicycle) <b>(0.97)</b>	Flows (R2-Bicycle) <b>(4.3%)</b>
Waiting time before diffusion (s)	60			
Min-headway (front/rear) (m)	0.5		Travel time (R1-MV) <b>(0.95)</b>	Travel time (R1-MV) <b>(2.2%)</b>
Safety distance reduction factor	0.6			
Maximum deceleration for breaking	-3		Travel time (R2-MV) <b>(0.98)</b>	Travel time (R2-MV) <b>(0.7%)</b>
			Travel time (R1- Bicycle) <b>(0.91)</b>	Travel time (R1- Bicycle) <b>(6.5%)</b>
			Travel time (R2- Bicycle) <b>(0.93)</b>	Travel time (R2- Bicycle) <b>(5.1%)</b>

### 3.3. Driving volatility impact on safety

The results of safety model (see Table 3) were in line with prior results for driving volatility (Section 3.1) in both case studies. Specifically, R2 recorded higher average speeds for both cyclists and MVs with values 17.1 km/h and 31.3 km/h, respectively. The number of bicycle stops at R2 is 8 times higher than R1, while R2 had nearly 90% more MV stops compared to R1. As suspected, R2 yielded 9 times more conflicts than R1, mostly due to the higher traffic volumes on that site, and it also had more severe conflicts. As long as TTC and PET decreased both the severity of traffic conflict and probability of potential crash increased (Gettman et al., 2008). R1 surprising yielded lower severe potential crashes since MaxS, DeltaS and DR (absolute values) were higher by 12%, 113% and 305%, respectively, compared to R2. This can be explained by high traffic volumes during peak hour which in turn lead to an occurrence of some traffic conflicts at moderate speeds. However, the difference in MaxS was not statistically different between roundabouts (p-value > 0.05) since speed distributions were similar between roundabouts.

Fig. 8 depicts the hotspot conflicts location for MV-bicycle and MV-MV in both studied cases. The results showed that conflicts in the approach area were more prevalent (since road users must yield) than the exit area of roundabouts. The number of lane change conflicts was considerable in the circulating areas of R1 and R2 mostly explained by weaving manoeuvres of vehicles before they leave roundabouts to the corresponding exit leg.

Table 3. Comparison between traffic performance and safety at R1 and R2.

Vehicle Class	Parameter	R1	R2	<i>p</i> -value
Motor vehicle	Number (vph)	1 518	1,642	~0.00
	Stops (vph)	812	1,526	~0.00
	Speed (km/h)	27.7	31.7	0.008
Bicycle	Number (bph)	251	185	0.002
	Stops (bph)	131	118	0.16
	Speed (km/h)	12.8	17.1	0.001
Motor vehicles and Bicycles	Total Conflicts (n)	117	1 202	~0.00
	Crossing	1	8	~0.00
	Lane Change	88	1 083	~0.00
	Rear End	28	111	0.002
	TTC (s)	1.2	1.1	~0.00
	PET (s)	1.8	1.1	~0.00
	MaxS (m/s)	5.4	4.8	0.53
	DeltaS (m/s)	3.4	1.6	~0.00
	DR (m/s <sup>2</sup> )	-1.6	-0.4	~0.00

Note: Shadow cells indicate that output measure is not statistically different at 95% confidence level (*p*-value<0.05).

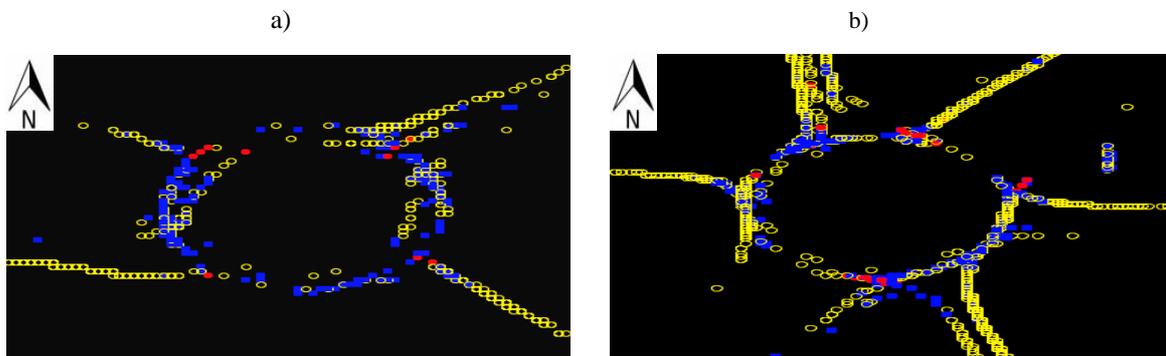


Fig. 8. Hotspot conflicts location for the R1 (left) and R2 (right).

Conflicts – Red colour, Lane Change - Blue colour, Rear End - Yellow colour)

#### 4. Conclusions and Policy Implications

The results of this paper were promising since speed variation and subsequently, acceleration/deceleration variation were showed to have influence on driving volatility for both bicycles and MVs at conventional two-lane roundabouts. However, motor vehicles yielded higher acceleration-deceleration variation than bicycles. It was also demonstrated that the frequency of MV-bicycle and MV-MV conflicts (up to 9 times), emissions per unit distance (9-15%, depending on the pollutant) and number of stop-and-go cycles (up to 8 times for bicycles and 90% for MVs) were higher at the roundabout with high traffic volumes and low cyclist activity.

It is well-known that emissions and acceleration-deceleration rates are intrinsically associated, but this paper takes a step forward and extends the analysis to the acceleration-deceleration variation (jerk) in different speed ranges and volatility impacts at multi-lane roundabouts.

The potential applications of this paper can include the development of quantitative surrogate measures for interaction between MV and cyclists at different roundabout layouts. This could be potentially used for proving real-time information for drivers, or warning surrounding cyclists using emerging connected vehicle technologies. This paper also supplied relevant information for transportation experts to better understand how MV-bicycle interactions can

influence traffic performance, safety, and emissions at two-lane roundabouts. It must be outlined that this type of roundabout represents specific problems for cyclists, since it allows vehicles to approach and negotiate at high speeds and enabling lane changing and weaving manoeuvres at the circulating and exit areas.

Therefore, future work will be focused on the analysis of this methodology for a larger number of roundabouts with different layouts (single-lane, compact two-lane and multi-lane), sizes and number of entry and exit legs. It is clearly imperative that driving volatility should include the comparison of different accommodation of bicycle in roundabouts (e.g., sharing bicycles with pedestrian or vehicles; dedicated bicycle lanes separated from pedestrian paths and motor vehicle lanes).

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