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**Pedestrian and Cyclists Impacts on vehicular Capacity and Emissions at different Turbo-roundabouts layouts**

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### Abstract

Presence of pedestrian crosswalks and cyclists at innovative configurations of roundabouts may result in an impedance effect on the available vehicular capacity of the intersection. The degree of this impedance is related to the likelihood of driver yielding at the crosswalk or bicycle dedicated lanes perpendicular to the movements of motor vehicles. However, little is known about the impedance effect and increase in emissions regarding the presence of pedestrians and cyclists at different turbo-roundabout layouts. The main objective of this paper is to quantify pedestrian and cyclist impacts on a turbo-roundabout corridor level. The study has two major purposes: 1) to evaluate the impact of several pedestrian and cyclists demands on corridor traffic performance and pollutant emissions; 2) to examine the effect of different driver yielding behaviour rates on both cyclist and pedestrian delay. Vehicle dynamics along with traffic, pedestrian and bicycle volumes data were collected from two turbo-roundabout corridors in the Netherlands. Microscopic modelling platforms of traffic (VISSIM) and emissions (Vehicle Specific Power and EMEP/EEA) were used to reproduce sites operations. Next, 72 combined pedestrian and cyclist demand scenarios according the corridor-specific characteristics were defined. Each volume scenario was then applied to scenarios with yielding rates of 100%, 80%, 60% and 40%.

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*Keywords:* turbo-roundabouts; driver yielding; pedestrians; cyclists; traffic modeling; emissions

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### 1. Introduction

Turbo-roundabouts are an increasingly common form of intersection control in the Netherlands and have been adopted in other European countries in the past decade (Dirk de Baan, 2016). They are recognized for providing a safe environment for both motor vehicles and vulnerable users (cyclists and pedestrians) (Corriere and Guerrieri, 2012). Turbo-roundabouts convey these benefits because they induce lower speeds of travel by virtue of its shape. They include curb raised dividers that separate the circulating lanes at the entry, circulating areas and exit of turbo-roundabout.

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Operational and emissions impacts of turbo-roundabouts in isolation are well documented but the impact on interdependent turbo-roundabouts in series along corridors may be different. The existing literature has been focused on the development of mathematical roundabout capacity models as a function of pedestrian flows and the assessment of impedance caused by pedestrians (Schroeder et al., 2012; Kang and Nakamura, 2015; Knoop and Daganzo, 2017). The Highway Capacity Manual contains several formulations that allow estimating the capacity-reducing effect of pedestrian crossings at roundabouts (HCM, 2010). Concerning cyclists, past research has been centred on the perception of their risk along roundabout influence areas (Daniels et al., 2008; Polders et al., 2015), and in testing different treatments to improve bicycle access and safety at roundabouts (Sakshaug et al., 2010). However, above studies did not include the analysis of crosswalks in innovative roundabouts layouts. Turbo-roundabout capacity and emissions widely depend on the conflicting traffic at the subject approach (Vasconcelos et al., 2014; Fernandes et al., 2016) but additional factors may compromise the efficiency of a turbo-roundabout, including the effect of pedestrian crossing or bicycle lanes close to the approaches. The research on capacity and emissions in turbo-roundabouts is extensive, either at isolated intersections (Vasconcelos et al., 2014; Lambertus and Serge, 2015) or at a corridor level (Silva et al., 2015; Fernandes et al., 2017), but does not deeply explored the influence of pedestrians and cyclists.

The impedance effect of pedestrian crossings at roundabouts can severely affect the available capacity of intersection owing to allocation of rights-of way (Findley et al., 2017). Given the same pedestrian or bicycle volumes, a higher propensity of drivers yielding to vulnerable users is likely to influence vehicular entry capacity and emissions. Despite these considerations, there is a dearth of knowledge about the relationship between the propensity of yielding to pedestrians or cyclists at turbo-roundabouts. The rate of driver yielding to pedestrians varies across locations but in nearly all cases do not reach 100% (Schroeder et al., 2012). For example, the propensity of driver yielding at two-lane roundabouts in the United States is about 45% (Salamati et al., 2013). With respect to cyclists, prior research conducted in Sweden documented a driver-yielding rate to cyclists of 58% at Swedish intersections (Silvano et al., 2015).

The review and synthesis of the technical literature reaffirms that there is a need to gain a better understanding of impedance effect of pedestrians and cyclists simultaneously on a turbo-roundabout, and to develop robust relationships between vehicle yielding rates, and different pedestrian and cyclist demand levels. Also, few information is available about the impedance effects of pedestrians and cyclists on interdependent and functionally turbo-roundabouts in series on an arterial. If spacing between intersections is not large enough, and pedestrian or bicyclist volumes are significant, then platooning and queue spillback effects will be particularly sensitive on upstream/downstream turbo-roundabout. This phenomenon does not occur at isolated turbo-roundabouts, and therefore it must be analysed. Thus, the motivation of this paper is to assess the pedestrian and cyclist impedance effects at urban turbo-roundabouts along corridors in terms of traffic performance and pollutant emissions. The developed relationships are expected to be sensitive to the propensity of drivers to yield to vulnerable users. The objective of this paper is two-fold:

- To assess several pedestrian and cyclist demand levels on number of stops, queues, and carbon dioxide (CO<sub>2</sub>), carbon monoxide (CO), nitrogen oxides (NO<sub>x</sub>) and hydrocarbon (HC) emissions along turbo-roundabouts;
- To address the effects on pedestrian and cyclists delay with variations in driver yielding behaviour rates.

## 2. Methodology

### 2.1. Site selection and data collection

The research team collected data to estimate capacity and emission impacts from two turbo-roundabout corridors in The Netherlands. The first corridor (N1) is near a commercial area of Gouda (Fig. 1-a). The total number of vehicles entering each turbo-roundabout ranged from 1,550 vehicles per hour (vph) to 2,700 vph during the evening peak period (5-6 p.m.). The site also has three bike-only use crossings where cyclists yield to motor traffic. Located in the residential area of Bergschenhoek, the second corridor (N2) has three turbo-roundabouts and includes a turbo-roundabout interchanges (TR3), as shown in Fig. 1-b. Entry traffic flow was approximately 1,500 vph and 1,970 vph in TR1 and TR3, respectively. All crossings are multi-use (pedestrians and cyclists) and vulnerable users have the right-of-way. The number of pedestrians ranged from 20 to 40 pedestrians per hour (pph) while bicycle volume exceeded 100 cyclists per hour (cph) in some crossings. It must be noted that TR3 at N1 and TR1 at N2 have one available lane for through traffic in one of the main approaches. Table 1 lists the information of each site.

Motor vehicles, pedestrian and cyclist volumes, and directional split distributions were gathered from overhead video in 5-min time intervals. Field experiments were carried out during the evening peak (4:00-6:00 p.m.) in May 2016. A passenger car equipped with a GPS data logger was used to record second-by-second speed, distance and slope. For this study, 200 GPS travel runs were extracted and identified (nearly 350 km of road coverage over 8 h). This number of runs for vehicle dynamic data collection and videotaping is considerable suitable (Fries et al., 2017).

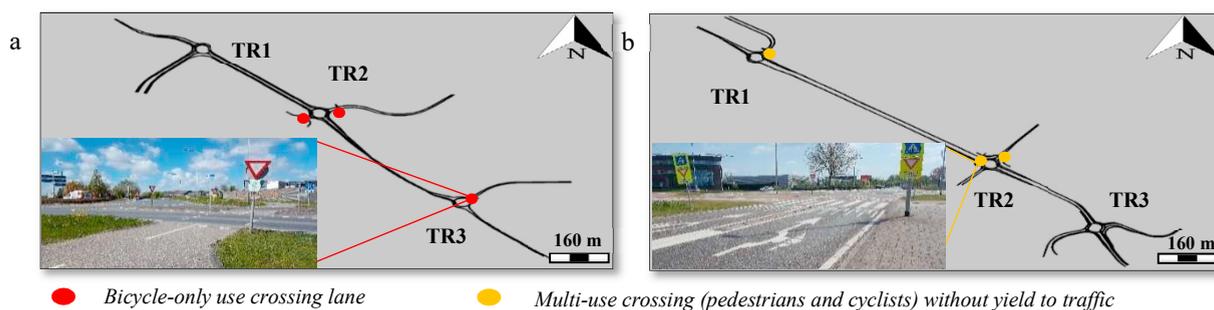


Fig. 1. Studied turbo-roundabout corridors with the location of candidate crossings: (a) N1; (b) N2.

Table 1. Summary of Study Corridor Characteristics.

Site	Turbo-roundabout	Layout (COWI, 2013)	Entry Traffic Flow [vph]	Pedestrians [pph]	Bicycles [cph]	Length of the corridor [m]
N1	TR1	Knee	450-1,170	<i>no pedestrian crossings</i>	<i>no bike crossings</i>	1,400
	TR2	Egg	150-1,060	<i>no pedestrian crossings</i>	35-65	
	TR3	Partial	420-670	<i>no pedestrian crossings</i>	55	
N2	TR1	Partial	250-760	<i>no pedestrian crossings</i>	140	1,300
	TR2	Egg	200-710	25-35	75-120	
	TR3	Basic	270-680	<i>no pedestrian crossings</i>	<i>no bike crossings</i>	

## 2.2. Traffic Model

The VISSIM microsimulation package can evaluate corridor operations in a given context of traffic, pedestrian or bicycle demands, directional split distributions and intersection layout (PTV AG, 2011). This traffic model was selected because it is recognized as a consistent tool for turbo-roundabout operations [e.g., (Fernandes et al., 2017)] and it includes a psychophysical gap-acceptance rules can reproduce the interactions between motor and non-motorized modes (PTV AG 2011). Simulation experiments were performed for the analysis period between 4:30 p.m. and 6:00 p.m. with a 30-min “warm-up” period prior to 5:00 p.m. The following Dutch fleet composition was considered (EUROSTAT, 2016; CBS, 2016): 70% Gasoline Passenger Vehicles (GPV), 15% Diesel Passenger Vehicles (DPV), 9% Light Diesel Duty Vehicles Trucks (LDDT) and 6% of Hybrid Electric Vehicles (HEV). Heavy Duty Vehicles (HDV) represented 7% of traffic along N1 corridor and were therefore included in the analysis. Remaining categories such as transit buses, motorcycles and HDV at N2 site were excluded because they only accounted for 1% of the fleet composition.

First, traffic, pedestrian and bicycle volumes were assigned for each link and according the corridor-specific split distributions. Second, GPS traces were matched to each coded link based on the geographic coordinates (GPS Visualizer). During this step, reduced speeds areas and desired speed decisions (PTV AG, 2011) were combined to match speeds as close as possible and to avoid excessive acceleration values in the traffic model. The speed distributions for cyclists ranged from 14 km/h to 35 km/h (COWI, 2013) while an average pedestrian walking speed value of 1.5 m/s was adopted (Chandra and Bharti, 2013).

The methodology for calibrating traffic model was done in three steps: *I*) Determine the minimum number of times to run VISSIM based on the variance of the mean and a tolerable error (Fries et al., 2017); *II*) Compare observed and estimated traffic, pedestrian and bicycle volumes and vehicle speeds using model default values; and *III*) Optimize model parameters using a genetic algorithm (Paz et al., 2015) with a calibration target of matching flow rates. The objective function was the minimization of the Normalized Root Mean Square (NRMS).

The widely-accepted Root Mean Squared Normalized Error (RMSNE) goodness of fit measure was used as the calibration criteria (Brackstone and Punzo, 2014; FDOT, 2014). RMSNE measures the percentage deviation of the estimated and observed link counts. A RMSNE lower than 15% was defined as the calibration target (FDOT, 2014). Along with the above steps, the model was validated by comparing estimated and observed average acceleration for each coded link, and using a different data set from the calibration procedure.

### 2.3. Emissions methodology

Turbo-roundabouts layouts have different localized effects on vehicles second-by-second speed trajectories and so that on the acceleration-deceleration profiles. These parameters are gathered from traffic model and used in VSP methodology as the basis for estimating CO<sub>2</sub>, CO, NO<sub>x</sub> and HC emissions associated with any speed trajectory (US EPA, 2002). Each VSP value estimated is categorized in one of 14 modes, and an emission factor for each mode is used to estimate the footprint of emissions for GPV (Fernandes et al., 2016), DPV and LDDT (Coelho et al., 2009), and HEV (Zhai et al., 2011). Still, the EMEP/EEA method was used to estimate HDV emissions (EEA, 2016) at the N1 corridor. Emission factors for diesel heavy-duty vehicles from Euro I to Euro VI emission standards are calculated as a function of the average speed. The generic functions and the values for the coefficients for these equations can be found elsewhere (EEA, 2016).

### 2.4. Design Scenarios

The effects of uniform pedestrian and cyclist growth were explored at two levels each: 1) for site N1, the number of bike users ranged from 50 to 750 cyclists per hour (cph) at each crossing with applying 100-cph increment; 2) for site N2, the volumes ranged from 50 to 450 pedestrians per hour (pph) and 50 and 450 cph at each crossing with 50-pph and 50-cph increments. It must be emphasised that higher values of pedestrian or bicycle volumes were not evaluated since both corridors were near saturation.

Each volume scenario was then applied to scenarios with yielding rates of 40%, 60%, 80% and 100%. For this study, varying driver yielding rates were modelled by creating a distinct vehicle composition for no-yield drivers. While normal vehicles yield to pedestrians and cyclists approaching the studied crossings, the no-yield vehicles were coded to yield only for cyclists and pedestrians directly in the crossing. Because no pedestrian activity was recorded at N1, only bicycle demand increments were explored in that site. Considering N2, the increments in pedestrian and bicycle demand were made simultaneously at the candidate crossings. Fig. 2 exhibits a flowchart that summarizes the 72 experimental treatments and factors in the modelling platform.

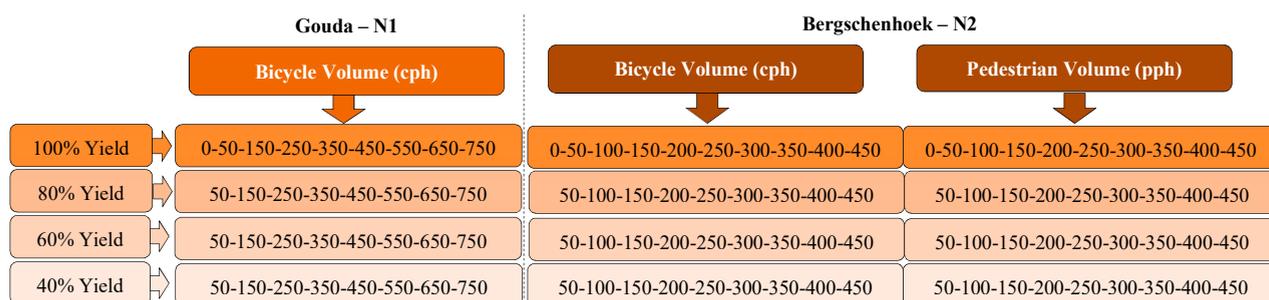


Fig. 2. Overview of design scenarios.

## 3. Results

### 3.1. Model Calibration and Validation

Fig. 3 (a-d) displays the main results for observed and estimated vehicle speeds using the default and calibrated model values for each corridor, and an additional 12 random seed runs (Fries et al., 2017). The GEH and NRMS statistics are also presented.

Using the default values (Fig. 3 a-c), linear trend lines matched the data with correlation coefficients of 0.74 and 0.83 at N1 and N2 sites, respectively. The scatterplots showed that initially model driver behaviour parameters underestimated vehicle speeds in some of the links. This may be due to fact that default standstill distances (PTV, AG, 2011) caused long queues and lower vehicle densities in some links. To address these issues, the research team optimized model driver behaviour to meet both the calibration criteria and the minimum NRMS. After this step, estimated speed values were notably improved, as illustrated in Fig. 3 (b-d). Additionally, RMSNE was much lower than 15% in both corridors (FDOT, 2014).

For validation, approximately 65% ( $R^2$ ) of estimated acceleration from VISSIM was predictable from the field accelerations at N1 and N2 sites leading to a reasonable fit between observed and estimated data.

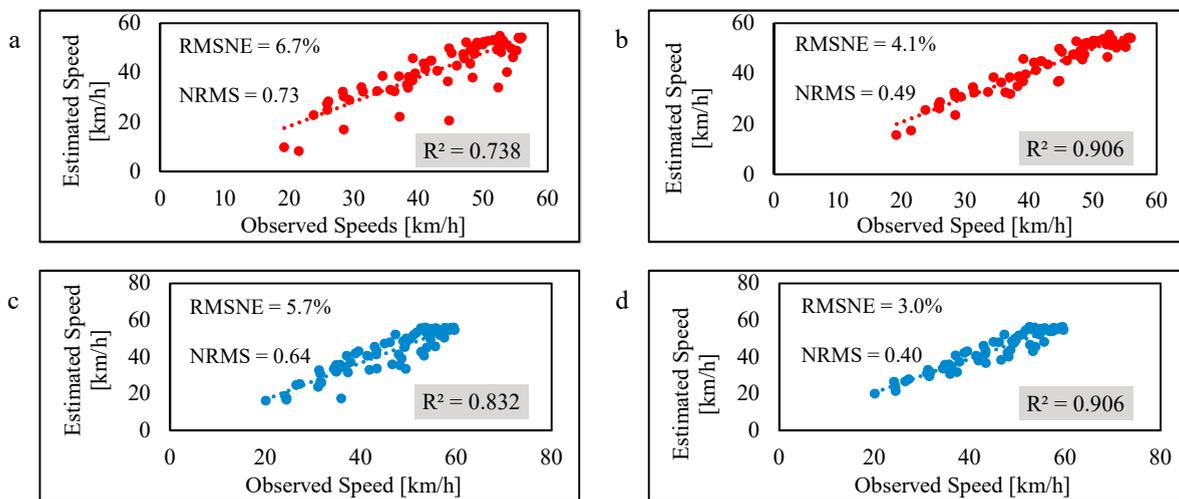


Fig. 3. Observed versus Estimated speed: (a) N1 - Default parameters; (b) N1 - Calibrated; (c) N2 - Default parameters; (d) N2 - Calibrated.

### 3.2. Effects of pedestrians and cyclists demand on capacity and emissions

This section discusses pollutant emissions and traffic performance with different pedestrian and bicycle demands. The team used actual volumes as the baseline for all traffic performance and emission analyses. The resulting  $\text{CO}_2$  and  $\text{NO}_x$  emissions, number of stops and queues are exhibited in Fig. 4 a-h.

The effect of cyclists on N1 operations becomes more severe only for higher cyclist volumes (>550 cph). This corridor with 650 cph by crossing for the 100% yielding case recorded 5%, 8%, 130% and 35% more  $\text{CO}_2$  emissions per unit distance,  $\text{NO}_x$ , number of stops and queues, respectively, when compared to the baseline conditions. Other pollutants (CO and HC) presented similar trends as  $\text{NO}_x$  and CO gases. The findings of the varying yield rates in Fig. 4 a-d surprising show small improvements. The reason for this slight effect was that most no-yield vehicles were delayed by yield vehicles, which was particularly sensitive at TR3 (only contained one lane for through traffic). Moreover, N1 has moderate flow rates in some of TR2 and TR3 approaches. As the yielding percentage decreases to 60% and 40%, it seems to be a trend toward less emissions, queues and number of stops. For instance, if 40% of drivers yield to cyclists with a demand for bicycles of 350 cph, then corridor reduced 1% and 8% of emissions ( $\text{CO}_2$  and  $\text{NO}_x$ ) and queues, respectively, when compared to the 100% yielding case.

Regarding N2 site, the results showed that the changes in yielding percentages from 100% to 40% had more impact on performance measures than the emission levels (Fig. 4 e-h). If each crossing has 250 cph and pph, the increase in the number of vehicle stops may be approximately 100% in relation to the baseline conditions while emissions may increase by only 4%. Overall, N2 operations were gradually improved as the yielding rates decreased which was different from N1 results. This happened because almost roads upstream/downstream of the studied crossings operated above saturation. Thus, no-yield drivers were less affected by yield drivers, even considered the mutual impedance effect of pedestrians and cyclists on traffic operations.

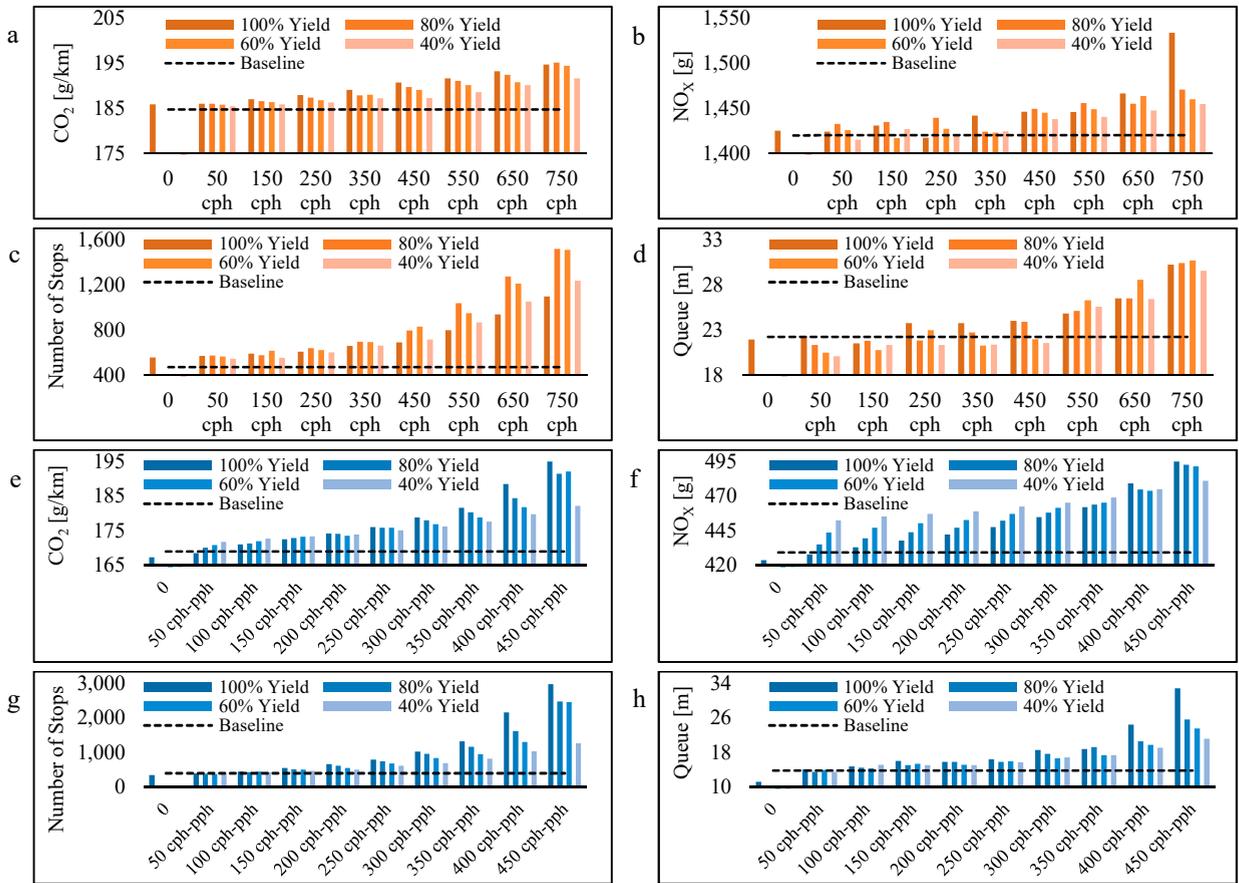


Fig. 4. Traffic performance and emissions results with different yielding rates: (a) N1 – CO<sub>2</sub> emissions; (b) N1 – NO<sub>x</sub> Emissions; (c) N1 – number of stops; (d) N1 – queue lengths; (e) N2 – CO<sub>2</sub> emissions; (f) N2 – NO<sub>x</sub> Emissions; (g) N2 – number of stops; (h) N2 – queue lengths.

Fig. 5-a revealed that the highest CO<sub>2</sub> emissions per kilometre at the N1 site were found at the downstream (95% higher than the average CO<sub>2</sub>) and upstream (70% above the average CO<sub>2</sub>) areas of turbo-roundabouts, and near the cyclist crossings. In such latter locations, cars that waited until cyclists completed the crossing, and stopped at the yield lane emitted more than 250 g/km for CO<sub>2</sub>. This was 30% more than the average N1 value (186 g/km). The findings from N2 site showed an identical trend (Fig. 5-b). CO<sub>2</sub> emissions along the downstream and near crossings were higher 120% and 80%, respectively, than the average N2 corridor value. Vehicles at the upstream of TR1 also generated high values of CO<sub>2</sub> emissions (+35%). This occurred for two main reasons: 1) moderate rate of left turning; and 2) TR1 has one lane available for through traffic, which results in lower capacity outcomes. The analysis of local pollutants (CO, NO<sub>x</sub> and HC) resulted in similar hotspot emission locations as CO<sub>2</sub> emissions for both corridors.

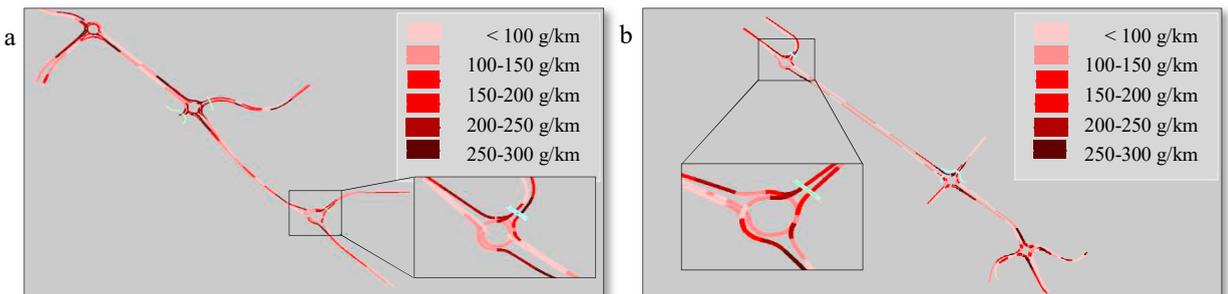


Fig. 5. Hotspot CO<sub>2</sub> Emissions locations for 100% yield case: (a) N1 – 250 cph; (b) N2 – 250 pph and 250 cph.

### 3.3. Impacts on pedestrian and cyclists delay

As the final evaluation component, the effect of various yielding scenarios on pedestrian and cyclist delay was explored. The results in Fig. 6 for N1 and N2 confirmed moderate cyclists or pedestrian delay at low yielding rates, since vehicles at the entry, exit or circulating areas of turbo-roundabout were unlikely to be stopped at the crossing. No large differences were observed among pedestrian and bicycles flow levels. For the 80% yielding case, the average delay per cyclist at N1 ranged from 1.2 s to 2.7 s on average with 50 cph and 650 cph, which was obviously very low. With very high cyclist and pedestrian volumes (> 450 cph and pph) and 40% yielding rates, few crossings opportunities were available for vulnerable users, thus causing delay up to more than 5 and 9 s on average at N1 and N2, respectively. This represented an increase of 130% on average at N2 comparing with 100% yielding case.

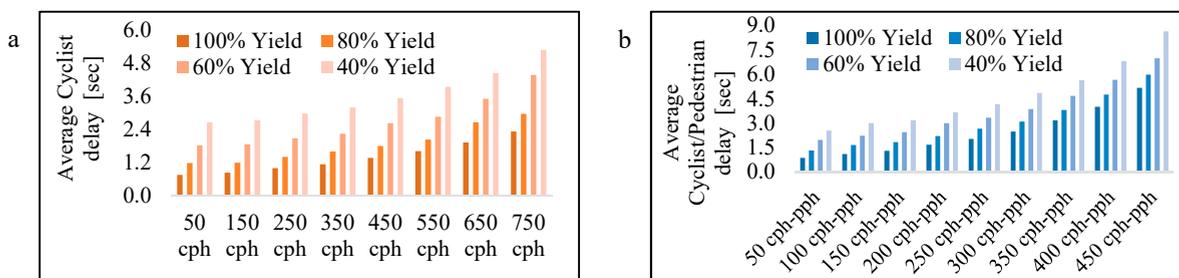


Fig. 6. Pedestrian and cyclists delay results for select scenarios: (a) N1; (b) N2.

## 4. Conclusions

This paper investigated pedestrian and cyclist effects on traffic performance and emissions at turbo-roundabout corridors as a function of driver yielding behaviour. A microsimulation environment was used to explore changes in bicycles and pedestrian flow rates and yielding parameters. The results confirmed that the effect of varying yielding rates in both traffic perform and emissions levels was only relevant under very high bicycle and pedestrian volumes (>450 cph and pph). For low or moderate values, yielding rates effect was small on corridors operations because most yield drivers delayed no-yield drivers when a pedestrian or cyclist passed at the crossing. It was also found that the pedestrian and cyclist impedance effect on traffic performance and emissions was (nearly) constant under low and moderate flow rates, but that varying yielding rates did tend to have an effect on pedestrian and cyclist delay.

This work contributed for solid knowledge about the combined effects of pedestrian and cyclists as vehicles point of view and simultaneously about the impacts of driver yielding behaviour on non-motorized performance. This fact is important because driving styles (e.g., yielding rates) may vary from country to country.

Future work will investigate the effects of pedestrians and cyclists as a function of different entry and conflicting traffic flows in turbo-roundabouts. A deeper investigation of pedestrian and cyclist crossing speeds and characteristics (e.g. genre, age, pedestrian with disabilities or no), and their relationships with vehicle delay, emissions and safety levels will also be explored. Finally, mathematical models for adequately quantify vehicular delay for various yielding rates may be needed for different turbo-roundabouts layouts.

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