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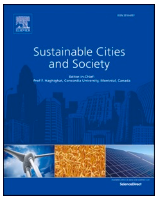

Can turbo-roundabouts and restricted crossing U-Turn be effective solutions for urban three-leg intersections?

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ABSTRACT

This research explored the potential of replacing conventional single-lane roundabouts by turbo-roundabouts and yield- and stop-controlled restricted crossing U-Turn (RCUT) at intersections located in urban corridors. A simulation approach based on a well-integrated assessment of traffic performance, emissions and driving volatility indicators of alternative intersection designs (AIDs) is therefore a major contribution of the study. The paper also addressed the impacts that several locations of the U-Turn crossovers have on travel and idling times, as well as on carbon dioxide and nitrogen oxides emissions. Traffic, pedestrian, and cyclist flow data were collected from two urban three-leg single-lane roundabouts. A microscopic simulation platform of traffic and emissions (respectively, VISSIM and vehicle specific power) was used to evaluate intersection-specific design and operations. The results indicated that turbo-roundabout and yield-controlled RCUT outperformed the existing single-lane roundabout at the two sites. Turbo-roundabout generally yielded the lowest travel times and emissions compared to the other intersections. The Yield-RCUT also performed better than the single-lane roundabout for U-Turn crossover located 100–170 m from the main intersection. Our findings bring a solid basis for academic research and transportation planners to promptly consider the implementation of AIDs and contribute to sustainable mobility in cities.

1. Introduction

Greenhouse Gas Emissions (GHG) and air pollution are recognized as critical issues worldwide that hinder the sustainability of cities and society (Perera et al., 2020). Despite the notable deployment in vehicle technology and growth in alternative fuel systems, road transportation still dominates urban emissions (Kazancoglu et al., 2021; Song et al., 2020). According to the European Commission, the European road transportation sector released more than 70% of the region's total transportation GHG (e.g., carbon dioxide – CO_2) in 2019 (EC, 2023), which in turn leads to global warming and climate change concerns. Also, road transportation is a major source of air pollution across Europe, being responsible for about 28% of nitrogen oxides (NOx) exhaust emissions in 2017 (EEA, 2021).

Several studies have indicated that conventional intersections in urban and suburban corridors are hotspot congestion, energy consumption and emissions locations (Meneguzzer et al., 2017; Zhang & Farooq, 2023). To alleviate their impacts, several strategies are adopted, such as the use of extra lanes (Dhatrak, Edara, & Bared, 2010) and signal-time signal synchronization, or coordination (Zhou et al., 2021). Adding more lanes on corridors in urban environments is a challenge because of land use constraints while cycle lengths and signal coordination only achieve slight improvements at congested intersections.

Roundabouts are a typical form of unsignalized intersection that are an effective traffic calming approach for improving mobility, environmental sustainability and safety levels compared with other forms of at-grade intersections (Ahmed & Easa, 2021). Albeit popular in urban areas, single-lane roundabouts cannot cope with daily traffic volumes higher than 25,000 vehicles, and they offer low capacity levels under higher pedestrian and cyclists volumes (Brilon, 2014; Rodegerdts et al., 2010).

Over the last three decades, alternative intersection designs (AIDs) have been increased in popularity in the United States (US) (Al-Omari et al., 2020; Claros et al., 2016; Jovanović & Teodorović, 2021; Reid &

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Hummer, 2001). Currently there are more than 400 AIDs implemented across the country with several more on the way (ITRE, 2022). These intersection types have the potential in improving the efficiency and safety of an arterial by removing one or more left-turn movements, which causes a reduction in the number of vehicle-to-vehicle conflicting points (ITRE, 2022). There is little research available on the effects of restricted crossing U-Turns (RCUT) on pollutant emissions or fuel consumption levels. Early studies claimed that AIDs can be associated with lower fuel consumption (Hughes et al., 2010).

The main objective of the study is to assess the potential benefits of replacing conventional single-lane roundabouts located in urban intersections by AIDs. These intersections include a turbo-roundabout, yield-controlled RCUT and stop-controlled RCUT. The overall traffic and emission performance of RCUT is hypothesized to be superior to that of an equivalent conventional single-lane roundabout. Because turbo-roundabouts, when located at intersections with high percentage of through or right-turn movements, have been shown to be performed environmental better than single-lane roundabouts (Vasconcelos et al., 2014), RCUT could lead to relevant CO_2 (global pollutant with impacts on climate change) and NOx (local pollutant with negative effects on human health) emissions savings if they are operated under identical traffic conditions.

To illustrate these predicted benefits, a microsimulation approach through PTV VISSIM together to Vehicle-Specific Power (VSP) emission method was applied. The modeling platform was calibrated with daily traffic data collected from two three-leg single-lane roundabouts located in the North of Portugal. These roundabouts have a high percentage of through traffic from main roads, and they often experience congestion problems on weekends, especially during late morning and early and late afternoon periods. This research concentrates on two types of RCUT – yield and stop-controlled (Hummer et al., 2014), and two turbo-roundabout designs (Fortuijn, 2009a), the latter ones suiting the intersection characteristics. The proposed intersection solutions are examined at different analysis levels: time periods (weekdays/weekend) and movement (major road/major road left/street road left/all roads U-Turn). The specific objectives include to:

1 Explore differences in travel time, delay, idling times, queue lengths, CO_2 and NOx emissions, and speed, acceleration, and vehicular jerk distributions between conventional single-lane roundabouts, turbo-roundabout and RCUT configurations;
2 Identify the hotspot emission locations along the influence area of turbo-roundabout and RCUT configurations;
3 Improve the intersection efficiency by testing various changes in RCUT design concerning the location of the U-Turn crossover.

Therefore, the contributions of the paper to the urban planning and transportation infrastructure topics may be valuable for the following reasons:

- One of the first studies focused on the implementation and comparison of different RCUT designs outside US context at urban intersections where traffic demand, split distributions and land use can favor their implementation. This will supply evidence-based facts for cities authorities and traffic planners so that they can start considering a wider use of these AIDs on an environmentally sustainable perspective;
- The application of an integrated impact assessment based on performance, energy, environmental and driving volatility indicators to examine different daily profiles concerning the functioning of single-lane roundabout, turbo-roundabouts and RCUTs that allow for a representation of a wide range of possible real-life situations, namely the variation in motor vehicles, pedestrians and cyclists' inflows, different vehicle type compositions or directional split distributions. It is worth to notice that most existing studies typically use these indicators separately and do not include the differences in daily profiles in their analysis.

2. Literature review

Studies of single-lane roundabouts in urban areas have shown that a proper design and modeling can improve their traffic operational and safety efficiency, and environmental sustainability (Ahmed & Easa, 2021; Coelho et al., 2006; Pilko et al., 2017).

A considerable part of the research that has been built upon modeling and simulation does not report a consensus about the emission benefits of single-lane roundabouts in comparison with other intersection forms. Some studies have shown that single-lane roundabouts have higher CO_2 and NOx emissions than multi-lane roundabouts (Vasconcelos et al., 2014) and traffic lights along arterials (Fernandes et al., 2015), and higher NOx emissions than yield regulated intersections (Várhelyi, 2002). Other authors conclude that isolated single-lane roundabouts are environmentally viable options over signalized (Várhelyi, 2002) and stop-controlled intersections (Mandavilli et al., 2008).

Few on-road emission studies have dealt with the comparison of single-lane roundabouts and other traffic controls. Gastaldi et al. (2017) reported a decrease in vehicle CO_2 emissions after replacing a signal-controlled intersection by a single-lane roundabout while Meneguzzer et al. (2017) concluded that a signalized intersection outperformed a single-lane roundabout in terms of NO_x criterion. Though other authors (Fernandes et al., 2020) referred that a suburban three-leg single-lane roundabouts with negligible conflicting traffic at main approaches achieved lower travel times and CO_2 emissions per kilometer than multi-lane and compact-two lane roundabouts, but it had higher NOx emissions per unit distance than the ML roundabout.

Past studies have demonstrated that AIDs decrease the likelihood of severe crashes (Al-Omari et al., 2020; ITRE, 2022). The best-known AIDs are diverging diamond interchange, median U-Turn, continuous flow intersection, quadrant roadway design, bowtie, jughandle, and superstreet (Hughes et al., 2010; Jovanović & Teodorović, 2021; Reid & Hummer, 2001).

Under certain traffic patterns, the improved safety and efficiency for congested corridors can be achieved by implementing superstreets, hereinafter referred to as RCUT (Hughes et al., 2010). This AID has been implemented in rural and urban corridors in more than ten states in the US (ITRE, 2022). RCUT differs from a conventional intersection by redirecting left-turn and through movements from minor-street entries. These movements must turn right to the major road, and after that make a U-Turn maneuver at a one-way median opening at least 400 feet (~120 m) downstream intersection (Hummer et al., 2014). RCUT typical layout does not change left movements that are possible from major roads, but its design can dispense the use of a directional cross-overs for left turning from the arterial at the intersection (Hughes et al., 2010), as shown in Fig. 1.

RCUT is adopted in cases of high through volumes on major roads with low left turning and low cross-street through and left demands, and it can be defined as a three-approach or four-approach intersection. The three types of RCUT intersections include signalized, yield-controlled, and stop-controlled. Agencies typically install sequential RCUTs along corridors, but RCUTs are often used as traffic control treatments at isolated intersections (Hummer et al., 2014).

Interest has been growing in the analysis of operational and safety benefits of RCUT intersections. Research on superstreets confirms that they are effective traffic control treatment for improving the progression of traffic at the main streets (Jovanović & Teodorović, 2021; Moon et al., 2011), decreasing average vehicle travel time through the intersection (Haley et al., 2011; Reid & Hummer, 1999), reducing intersection-specific delay and number of vehicle stops (Moon et al., 2011), increasing capacity (Hummer, 2008), and improving safety performance (Chase et al., 2020).

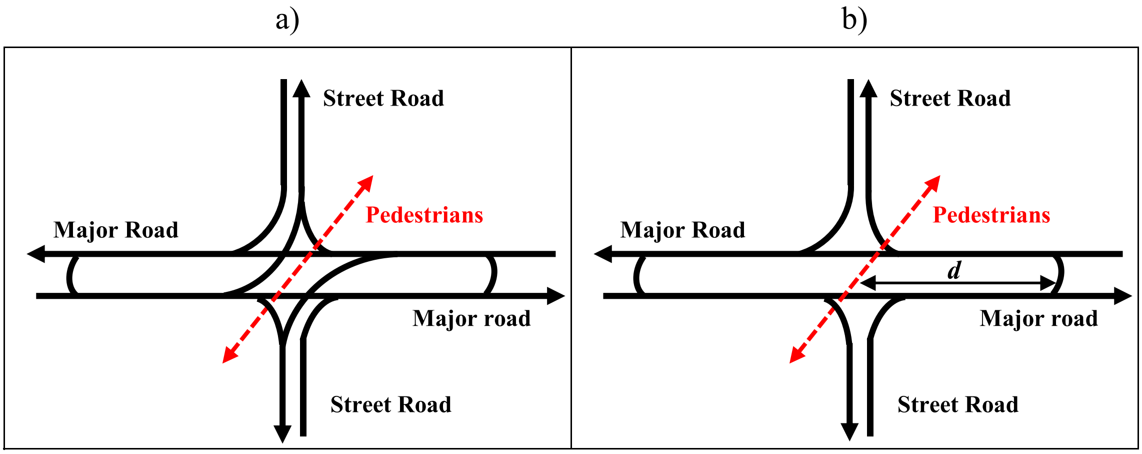

Fig. 1. RCUT schematic: (a) with direct left turns from arterial; and (b) without direct left turns from arterial.
Note: *d* represents the distance from the main intersection to the U-Turn crossover

RCUT also poses both benefits and challenges to pedestrians and bicyclists crossing at intersections. Its design provides less vehicle-pedestrian conflict points than conventional intersection designs due to the shorter and direct paths at pedestrian crossings. However, the use of diagonal cross through the direct left turns can present serious safety concerns for visually impaired pedestrians (Hummer et al., 2014). Holzem et al. (2015) suggested that the combination of the diagonal cross with the midblock cross is the recommended configuration for pedestrians at RCUT intersections while the recommended options for bicyclists are a combination of the bicycle direct cross and the midblock cross. There are other perceived disadvantages associated with the RCUT design, such as increased delay and travel distance for cross-street through traffic and for one pair of left turns, and requirement of a wide median to allow large vehicles to make safely U-Turns (Hummer, 1998).

Turbo-roundabout can be seen as a part of a menu of unconventional intersection designs that has been stood out, and proven its acceptance and popularity in several European countries (Tollazzi, 2014). Turbo roundabout is an arrangement of conventional two-lane roundabout where drivers have to select their entry lane in advance to negotiate and leave the intersection via the previously selected lane (Fortuijn, 2009a). It includes curb raised dividers that do not allow for both lane changes and cut-offs and located several meters before entries and beyond exits and along circulating area. Fortuijn (2009a) described five variations of the turbo roundabout: basic, egg, knee, spiral, and rotor. Some authorities have been recently transposed turbo-roundabout to the US context (Wankogere et al., 2017). Turbo-roundabouts are reported to be effective traffic control in reducing the number of traffic conflicts (Fortuijn, 2009a; Vasconcelos et al., 2014). These safety benefits are mostly due to the elimination of weaving conflicts in the two-lane layout, especially when drivers do not keep to their lanes while exiting intersection. However, past studies have been unable to reach a consensus about the benefits of turbo-roundabout regarding the intersection-specific capacity and emissions. Turbo-roundabout generally loses its performance as far as saturation flow rate and left-turning movements increase (Fernandes et al., 2017; Giuffre` et al., 2009; Silva et al., 2015; Vasconcelos et al., 2014). There are other factors influencing turbo-roundabout performance, such as geometry (Elhassy et al., 2021; Fernandes, Rouphail, et al., 2017), correct use of the inner lane (Fortuijn, 2009b) or pedestrian and bicycle volumes (Fernandes & Coelho, 2017).

The review of state-of-art shows few research studies focused on the energy and emissions performance of RCUT design, and none have compared the predicted impact of different RCUT configurations and turbo-roundabouts at intersections located at urban corridors. Therefore, it is necessary to pay attention to the critical aspect of the intersection design to mitigate traffic-related congestion, emissions, and safety in urban infrastructure.

3. Methodology

The research methodology involved a combination of field data analysis and microscopic modeling (Fig. 2). First, the analyst collected traffic, pedestrian, cyclist volumes and vehicle dynamic data in the candidate single-lane roundabouts (Section 3.1). Subsequent to the field work, the VISSIM microscopic traffic (PTV, 2022) was used to model each roundabout, and then calibrated and validated according to the site-specific operational conditions (Section 3.2). After that, several scenarios concerning the implementation of turbo roundabout and RCUT configurations were implemented and evaluated (Section 3.3). VSP (USEPA, 2002) method was paired with VISSIM to assess and compare pollutant emissions, traffic performance, and driving volatility-related variables between single lane roundabouts and proposed intersection configurations.

3.1. Data collection

Two single-lane roundabouts (S1 and S2) installed along an urban coastal corridor were sought out for this study (Fig. 3). The candidate studies are located in the urban area of Esposende, Portugal, with a population density of 358 inhabitants/km^2 and approximately 138 thousand overnight stays in 2019 (INE, 2021). Both roundabouts mostly serve through traffic (northbound and southbound) with a low percentage of left-turning movements, and low traffic volumes at street roads. S1 provides connection between city center and north beach areas while S2 is near to several business and service areas. Both roundabouts are the main access to the city from north and south directions. Regarding speed control, major and minor roads have a 40-kph speed limit. Main roundabout geometric characteristics are indicated in Table 1.

Although roundabouts have spare capacity during most periods, they inadequately operate during certain days, especially on weekends due to high traffic and pedestrian demand, as well as many cyclists sharing the road with motor vehicles. S2 also presents poor alignment of approach legs at major roads that is offset to the right of roundabout's center point.

Field data for S1 and S2 were both collected for 24 h period on a typical weekday (Thursday) and weekend (Sunday) in May and June 2022 under dry weather conditions. Two GoPro cameras were installed at strategic points to capture all movements and crossings of the studied intersections. After that, data were manually extracted to obtain movement counts in 15-min intervals for the following modes: light duty vehicles (LDV), light duty trucks (LDT), transit buses, heavy-duty trucks (HDT), pedestrians and cyclist flows at each roundabout crossing by traveling direction, and cyclists flow through intersections.

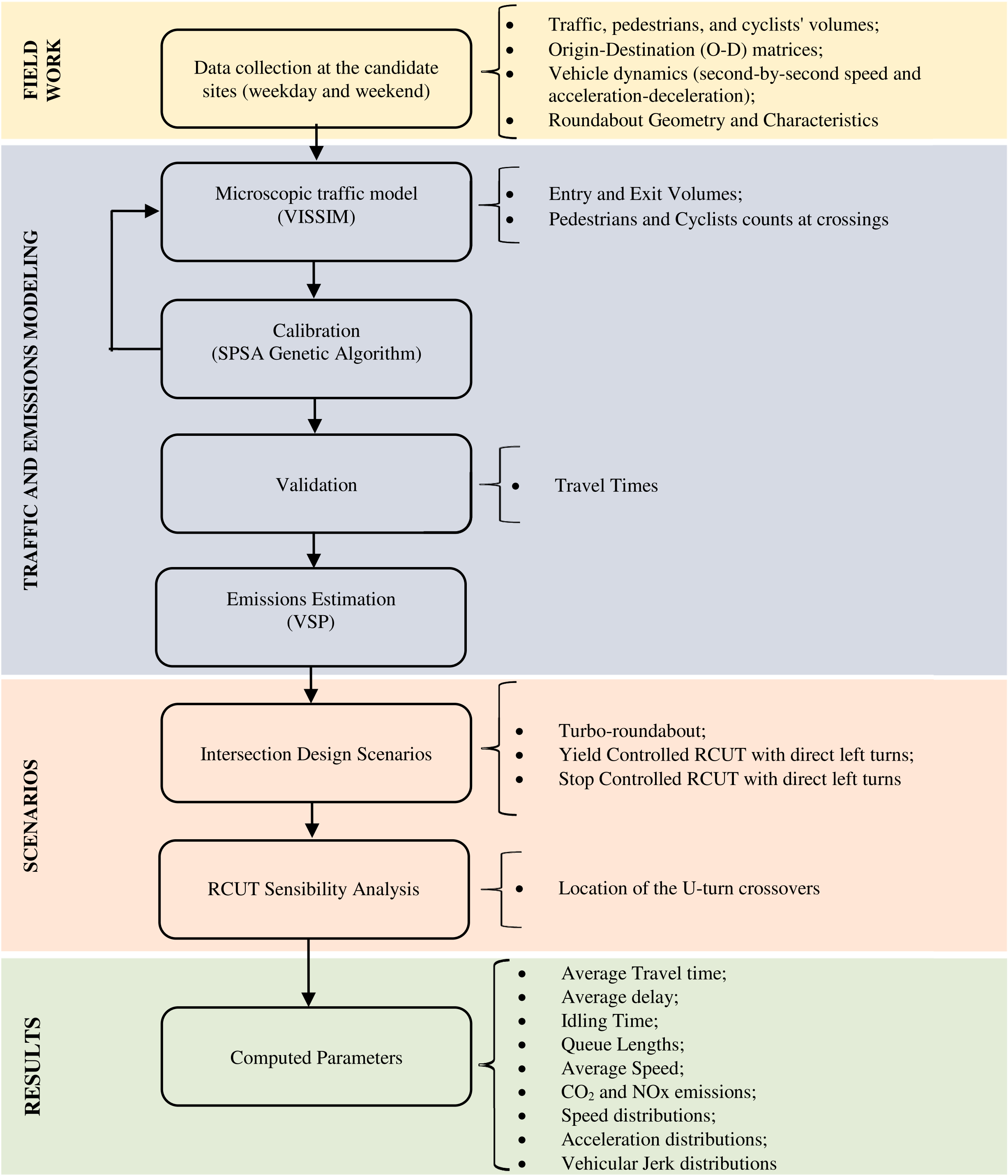

Fig. 2. Methodological Framework.
Legend: SPSA - Simultaneous Perturbation Stochastic Approximation;

Global Navigation Satellite System (GNSS) and On-board diagnostic (OBD) data were also collected from two test LDVs to record vehicle speed, distance traveled and deceleration-acceleration in 1 s intervals under free-flow conditions (6-7 a.m.), and during morning (8-10 a.m.) and afternoon (5-7 p.m.) peak periods. Two male experienced drivers (36 and 47 years old) performed several roundabout movement (L1-L3, L1-L2, L2-L1, L2-L3, L3-L1 and L3-L2) with different behavior types, i.e. calm, normal, and aggressive (Ferreira et al., 2021) to obtain a wide range of driving conditions. Total data collected included 153 GPS travel runs, which corresponded to a road coverage of approximately 10,000 s and 85 km. The resulting traffic and travel time data were further used for calibration and validation purposes in Section 3.2.

A preliminary inspection of the incoming traffic showed low traffic and/or pedestrians' volumes from 10:00 p.m. to 6:00 a.m. Thus, data for these periods were excluded from the analysis.

The peak period entering traffic at the S1 site occurred between 5:00

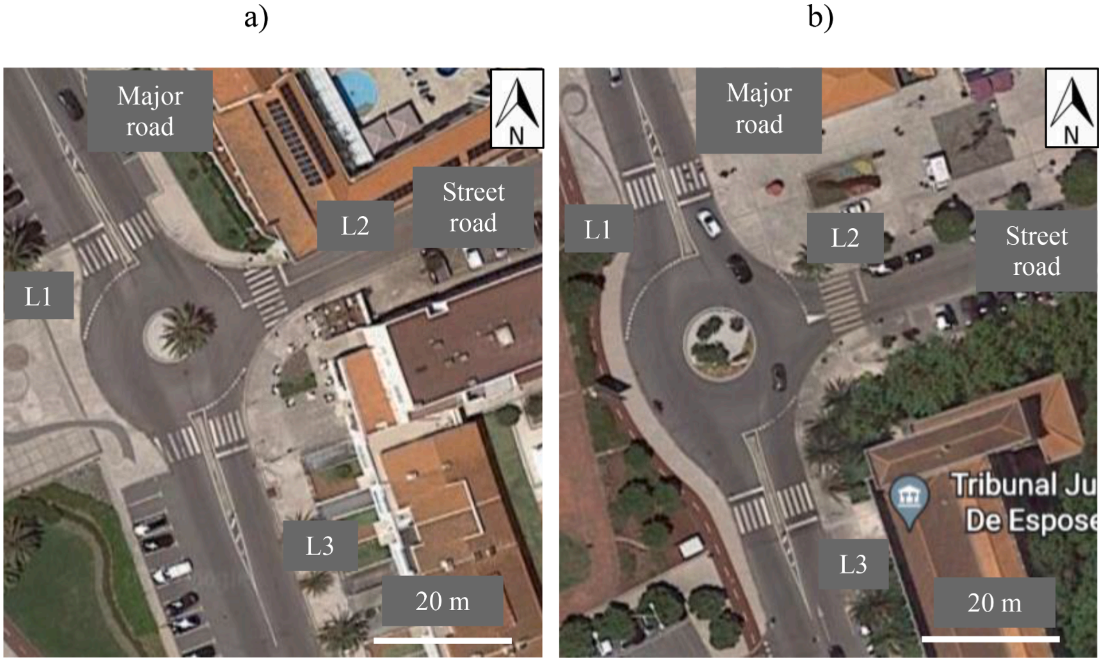

Fig. 3. Aerial view of the candidate roundabouts with legs identification: (a) S1; and (b) S2. [Source: Google Maps]

Table 1
Key Characteristics of selected roundabouts.

ID	GPS Coordinates	Inscribed circle diameter [m]	Central island [m]	Leg	# Entry lanes	# Exit lanes	Entry width [m]	Exit width [m]
S1	41.54012614, -8.786762535	23.5	7.6	L1	1	1	7.4	6.0
				L2	1	1	5.6	5.3
				L3	1	1	5.6	6.8
S2	41.53226710, -8.783230885	26.9	10.6	L1	1	1	8.5	5.8
				L2	1	1	5.6	4.3
				L3	2	1	5.8	8.5

p.m. and 7:00 p.m. on the weekday (Fig. 4-a), and between 4:00 p.m. and 6:00 p.m. on the weekend (Fig. 4-b). Overall, the daily entry flow during the weekend was 22% higher than did weekday. L1 and L2 dominated vehicular movements, contributing together with more than 93% of the entry flows on both days. The O-D matrices, in relative terms, were constant during the selected periods, and the percentage of U-Turns was very low ($<$ 1%). For each day, the through and left directional splits in the L1 were as follows: 5% and 94%, respectively, for the weekday; 4% and 94%, respectively, for the weekend. This roundabout has spare capacity during most demand periods because approximately 30% of L2 traffic goes right, thus facilitating the entries from the L1 and L3 approaches.

Concerning the pedestrian and cyclist counts, the experimental data showed daily numbers of 1,019 (Fig. 4-c) on weekdays and 1,258 on weekends (Fig. 4-d). The period from 3:00 p.m. to 7:00 p.m. was characterized by higher pedestrian and cyclist activity. Pedestrians represented roughly 95% of counts at the S1 crossings.

S2 exhibited different weekday and weekend traffic flow profiles. The most congested periods on weekday and weekend were between 5:00 p.m. and 7:00 p.m. (Fig. 5-a), and between 3.00 p.m. and 5:00 p.m. (Fig. 5-b), respectively. These periods contributed to approximately 20% of the total entry flow. It can be noted a peak in traffic volumes during the late morning on the weekend. Although L1 and L3 still appeared as relevant movements along S2, the street road L2 represented 13% and 15% of entry traffic on weekday and weekend, respectively. A close view of the directional split distributions showed an appreciable percentage of left turning at L1 entry, which accounted for nearly 10% of daily vehicular movements on weekday and weekend.

The analysis of weekday pedestrian and cyclist data indicated slight variations in the counts during working hours (9:00 a.m. – 6:00 p.m.), as shown in Fig. 5-c. For the weekend, several peaks in traffic volumes ($>$ 1,000 hourly counts) were observed in the late morning (10 a.m. – 12:00 p.m.) and afternoon (3:00 p.m. – 7 p.m.) periods (Fig. 5-d).

Fig. 6 illustrates the modal share for each roundabout approach and day. This set of field measurements allowed some conclusions to be drawn. First, LDV was the dominant mode regardless of the intersection, but its weight on total fleet was higher on weekend (95% or higher) than on weekday (89% or lower). Second, the percentage of cycle riders sharing road with motor vehicles was higher on weekend (1.1–2.4%, depending on the site) than did weekday (0.5-0.6%, depending on the site), which may result in more interactions between these modes and increased risk driving behaviors associated with changes in vehicle speeds, acceleration, and vehicular jerk (Fernandes et al., 2021).

Table 2 lists the average delay and level of service (LOS) for all vehicle movements across the S1 roundabout. These metrics were computed using aaSIDRA model (Akçelik, 2014) calibrated with local driving habits for roundabouts, namely: critical gap and follow-up times of 3.5 and 2.3 s (Vasconcelos et al., 2013), respectively. The S1 site is characterized by free-flow (LOS A) and stable traffic flow (LOS B), regardless of the approach and day. All traffic movements underwent slight variations in the average delay. The S2 site also operated with similar conditions during the weekday, the level of comfort and convenience of traffic decreased in some periods on the weekend (Table 3). For instance, L1 was assigned LOS C from 3 p.m. to 7 p.m., which represents control delay values higher than 21 s per vehicle. This is explained by high pedestrian and cyclist activity during these hours

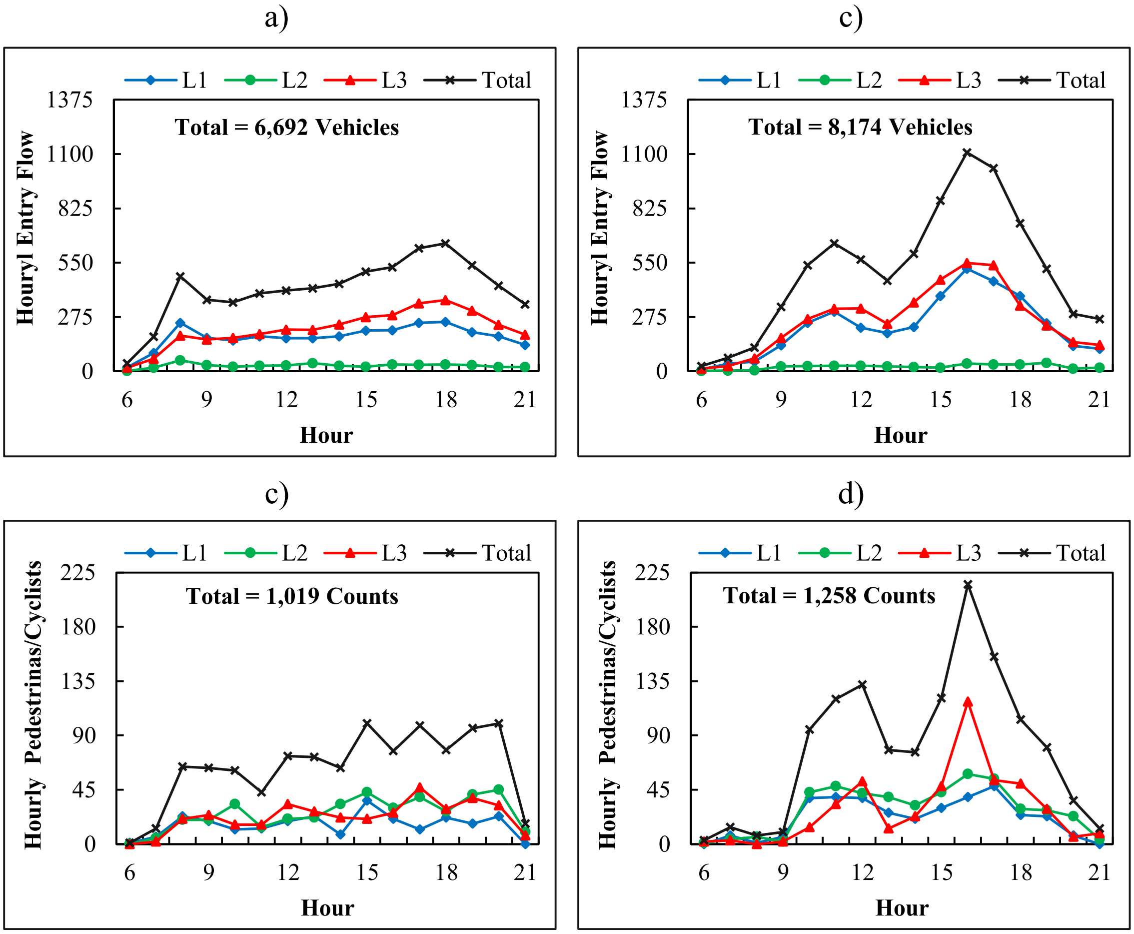

Fig. 4. S1 Demand: (a) Entry Flows (including cyclists flow through intersections) – Weekday; (b) Entry Flows (including cyclists flow through intersections) – Weekend; (c) Pedestrians/Cyclists at crossings – Weekday; and (d) Pedestrians/Cyclists at crossings – Weekend.

(Fig. 5).

3.2. Modelling platform

Microscopic simulation of roundabout operations was developed by VISSIM 2022 software (PTV, 2022). This model was chosen because it allows to: (i) simulate reliable interactions among motor vehicles, pedestrians and cyclists at roundabouts, which in turn yields the analysis of different traffic control treatments based on traffic performance, emissions and driving volatility indicators; (ii) define driving behaviors based on individual vehicle type and category, and intersection location (approach, circulating area, exit and crosswalk area); and (iii) calibrate traffic, speed and acceleration and directional split distributions data to produce realistic results of roundabout operations (Bahmankhah et al., 2022; Fernandes et al., 2017; Li et al., 2013; Schroeder et al., 2012). Past studies have successfully used VISSIM for operational analysis of single-lane roundabouts (Fernandes et al., 2017, 2015), turbo-roundabouts (Elhassy et al., 2021; Fernandes & Coelho, 2017; Fernandes et al., 2017) and RCUT configurations (Holzem et al., 2015; Moon et al., 2011).

3.2.1. VISSIM construction

Link coding was executed following recommended practices for roundabouts to ensure realistic emission analysis of road traffic (Fontes et al., 2015). The research team adopted a minimum link length in such a way that each vehicle spent at least 1 second in each link. This time fraction represents the resolution of the emission method and the basis for vehicular jerk computation, as explained in the following sections. The treatment of yield behavior at the roundabout entries used the Priority Rules tool of the VISSIM model (PTV, 2022) using a critical gap time value of 3.5 s (Vasconcelos et al., 2013). For roundabout exits and crosswalk areas, the Conflict Area tool of the model was applied (PTV, 2022). To account the effect of upstream queues, simulation considered an intersection influence area of approximately 250 m in each direction (Fig. 7). The modeling of on-street parking in the influence area of roundabouts was ignored.

To best model the interaction of pedestrians and bicyclists with motor vehicles at crosswalks, crosswalk configurations were coded using link behaviors named “crossing”. This type of behavior allowed pedestrians and cyclists to overtake freely each other. One lane in each traveling direction was defined for each roundabout crosswalk. Because bicycles traveling on the roadway were simulated, link behavior types at road street level allowed motor vehicles to overtake cyclists within a lane at downstream and upstream areas of intersections. The following travel speeds were adopted: (i) 4–7 $km.h^{-1}$ (Chandra & Bharti, 2013) for pedestrians and cyclists at crosswalks; and (ii) 15–25 $km.h^{-1}$ (Rodegerdts et al., 2010) for cyclists who use the motor vehicle lanes and travel at circulating area of roundabouts.

3.2.2. Number of simulation runs

As per VISSIM guidelines followed by Elhassy et al. (2021), an initial ten simulation runs with different random seeds were carried out to obtain initial results from the current site conditions, including average and standard deviation of traffic volumes at the entries and exits of the S1 and S2. After that, the research team used the equation outlined in Federal Highway Administration’s toolbox (Dowling et al., 2004) to

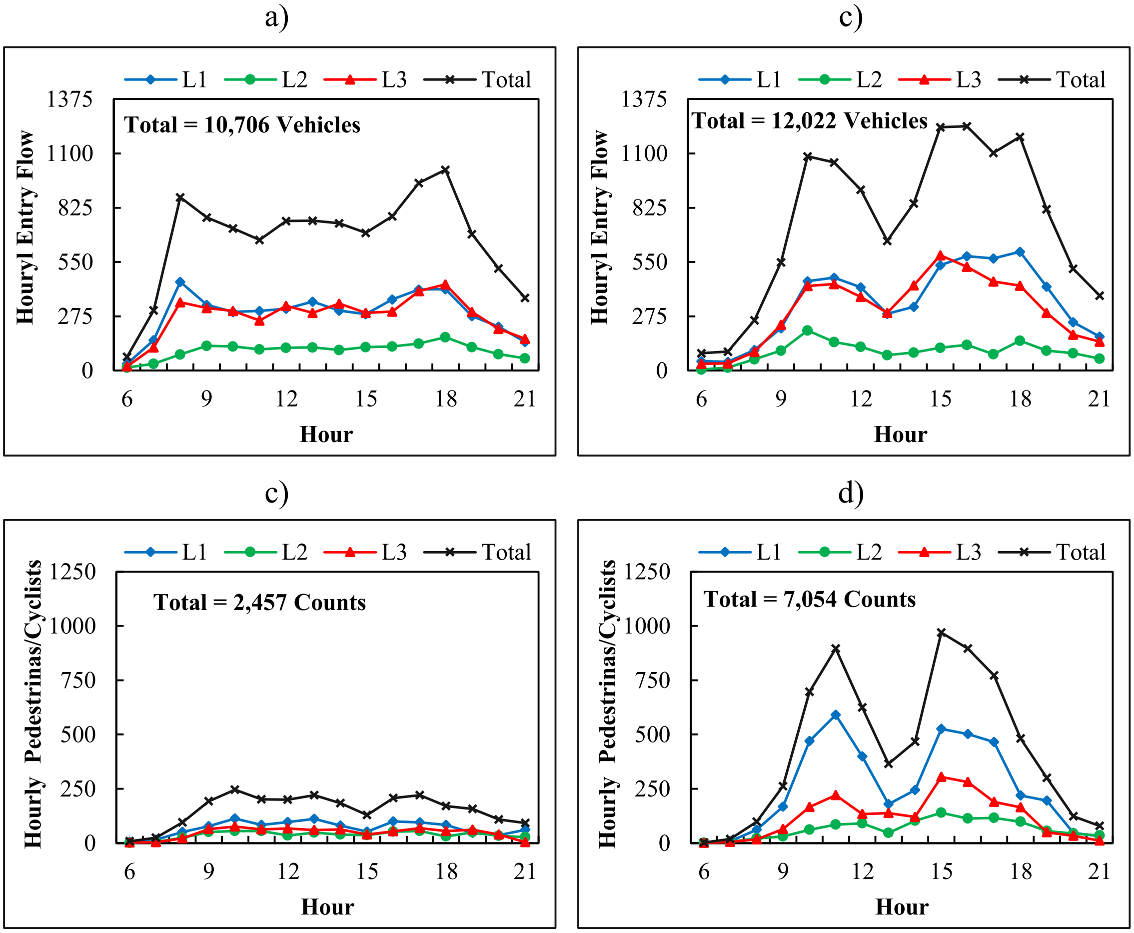

Fig. 5. S2 Demand: (a) Entry Flows (including cyclists flow through intersections) – Weekday; (b) Entry Flows (including cyclists flow through intersections) – Weekend; (c) Pedestrians/Cyclists at crossings – Weekday; and (d) Pedestrians/Cyclists at crossings – Weekend.

determine the minimum number of runs with a 95% confidence level at most critical locations at S1 and S2, namely the L3 entry. It was found that less than eight runs assured that microsimulation model results replicate adequately site-specific traffic operations, regardless of the location and day. Thus, VISSIM models were run nine times using the same different, random seeds.

3.2.3. Model calibration and validation

The traffic model was calibrated and validated using different data sets. The calibrated data included entry and exit volumes, direction-split distributions, cruise speed distributions, and free-flow speed distributions at the entries, exits and circulating areas, and acceleration and deceleration distributions. Because VISSIM operates stochastically, speed and acceleration distributions were modeled based on minimum, 25th, 50th and 75th percentiles, and maximum values acquired from data collection in Section 3.1.

The model was calibrated in two phases. The first adjusted multiple sets of runs of VISSIM driving behavior parameters to evaluate their impacts on traffic flows for each roundabout entry and exit leg. VISSIM parameters tweaked in the calibration included those of Wiedemann 74 car-following model (average standstill distance, additive part of safety distance, and multiple part of safety distance), minimum gap time, time before diffusion, front gap, rear gap, lateral distance, and simulation resolution (PTV, 2022). These model parameters were selected due to their impacts on operational levels of roundabout, which in turn impact on pollutant emissions, as reported by previous studies (Fernandes et al., 2017, 2015). During this phase, the research team maintained the same shape of the speed and acceleration distribution curves during the evaluation period but changed the mean values according to the site-specific conditions. The second step optimized those parameters using Simultaneous Perturbation Stochastic Approximation (SPSA) genetic algorithm. The objective function of that procedure was to minimize the Normalized Root Mean Square (NRMS). NRMS was defined here as the sum over all 15 min calibration periods of the average of the sum over all entries and exits of the roundabouts of the root square of the normalized differences between observed and estimated traffic volumes (Fernandes et al., 2017, 2018). For calibration criteria, the Geoffrey E. Havers (GEH) statistic is a heuristic formula used in the field of transportation planning to assess goodness of fit. GEH index of less than 4 at least 85% of the monitoring points is considered a good fit between observed and estimated (simulated) volumes (Dowling et al., 2004).

The models were validated using travel time as the comparison between VISSIM and the field data with the optimal calibrated parameters for each roundabout and day. Travel time was computed using a different speed data set from the calibration procedure that were collected during peak periods.

Fig. 8 shows the field (observed) and simulated traffic volumes after calibration of the traffic model by roundabout and testing day. All monitoring points (356) achieved GEH values lower than 4, which is compliant with the above-mentioned calibration criteria (Dowling et al., 2004). The NRMS values ranged from 0.175 to 0.203 in the S1 and from 0.125 to 0.129 in the S2. The differences between simulated and observed pedestrians and cyclist volumes at crossings showed differences below 0.5%. The analysis of optimal driving behavior parameters confirmed that the Wiedemann 74 car-following parameters change slightly according to the roundabout and day while time before

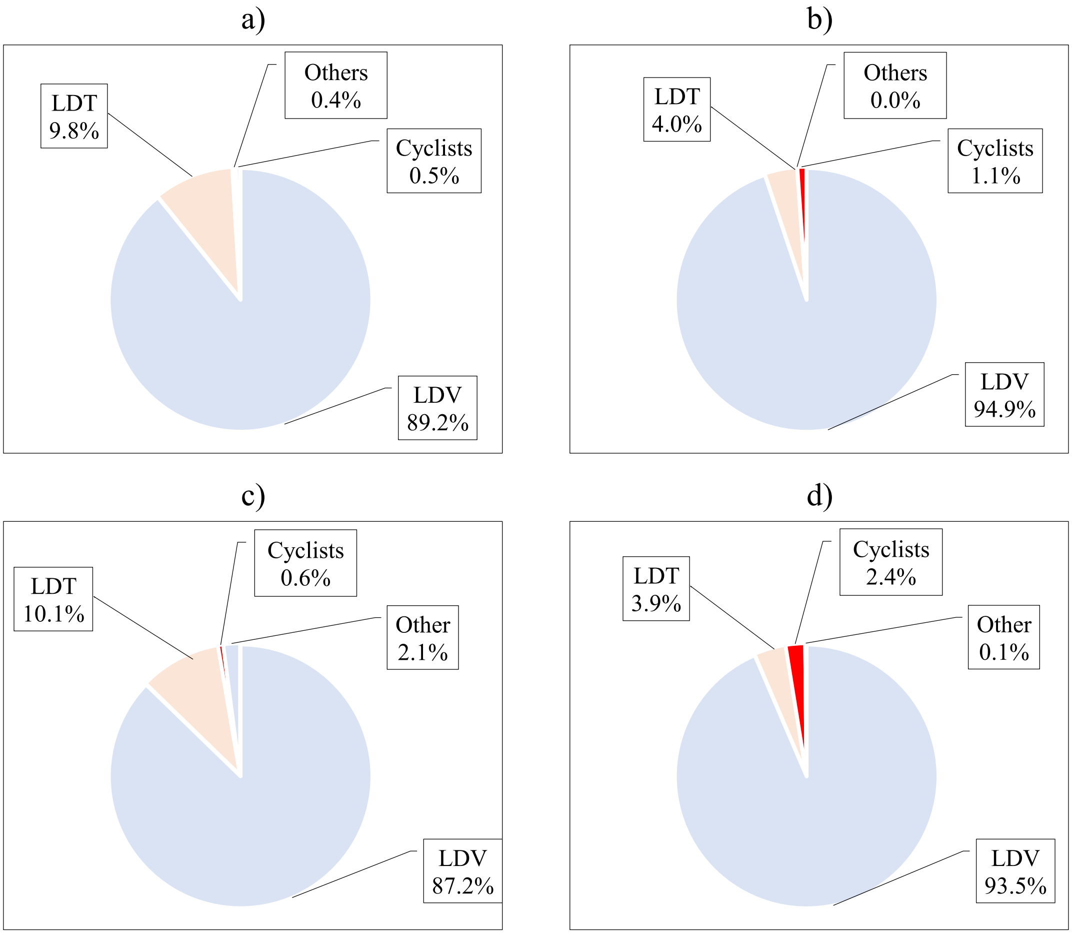

Fig. 6. Mode Share: (a) S1 – Weekday; (b) S1 – Weekend; (c) S2 – Weekday; and (d) S2 – Weekend.

Table 2
Average delay and LOS scheme for the S1 roundabout.

Hour	Weekday								Weekend							
	L1		L2		L3		Overall		L1		L2		L3		Overall	
	Delay (s/veh)	LOS	Delay (s/veh)	LOS	Delay (s/veh)	LOS	Delay (s/veh)	LOS	Delay (s/veh)	LOS	Delay (s/veh)	LOS	Delay (s/veh)	LOS	Delay (s/veh)	LOS
6 a.m.	3.7	A	3.6	A	3.7	A	3.7	A	3.6	A	3.6	A	3.6	A	3.6	A
7 a.m.	4.4	A	3.9	A	4.3	A	4.3	A	3.8	A	3.6	A	3.8	A	3.8	A
8 a.m.	6.2	A	4.4	A	5.4	A	5.7	A	4.1	A	3.7	A	4.0	A	4.0	A
9 a.m.	5.3	A	4.1	A	5.2	A	5.1	A	4.8	A	4.1	A	5.2	A	4.9	A
10 a.m.	5.1	A	4.1	A	5.2	A	5.0	A	6.7	A	4.6	A	7.0	A	6.8	A
11 a.m.	5.3	A	4.2	A	5.4	A	5.3	A	6.7	A	4.7	A	7.0	A	6.8	A
12 p.m.	5.2	A	4.2	A	5.7	A	5.4	A	5.8	A	4.5	A	6.9	A	6.3	A
1 p.m.	5.3	A	4.3	A	5.6	A	5.3	A	6.0	A	4.2	A	6.0	A	5.7	A
2 p.m.	5.3	A	4.4	A	5.9	A	5.6	A	5.8	A	4.6	A	7.4	A	6.7	A
3 p.m.	5.7	A	4.3	A	6.4	A	6.0	A	7.9	A	5.0	A	9.5	A	8.7	A
4 p.m.	5.7	A	4.5	A	6.5	A	6.1	A	10.8	B	5.8	A	12.0	B	11.2	B
5 p.m.	6.1	A	4.6	A	7.4	A	6.7	A	9.3	A	5.6	A	11.3	B	10.2	B
6 p.m.	6.7	A	5.0	A	8.9	A	7.9	A	9.1	A	4.9	A	8.3	A	8.6	A
7 p.m.	6.6	A	4.4	A	5.6	A	6.1	A	5.8	A	4.3	A	5.7	A	5.7	A
8 p.m.	5.3	A	4.2	A	6.0	A	5.6	A	4.7	A	3.9	A	4.9	A	4.8	A
9 p.m.	4.8	A	4.1	A	5.3	A	5.1	A	4.6	A	3.9	A	4.8	A	4.6	A

diffusion, lateral distance and simulation resolution parameters did not affect calibration results (Table 4). S2 yielded lower minimum values of gap time, and lower front and rear gap times than S1.

Although VISSIM output generally exhibited lower travel times than field travel times (Table 5), the optimal calibration setups produced acceptable targets for comparing model and observed travel times (Elhassy et al., 2021); the relative differences between simulated and observed values were lower than 16%. The Mann-Whitney U tests confirmed that the median travel times between simulated and observed groups were not statistically significant at 95% confidence level for all movements (p-values were equal or higher than 0.064). These calibration settings were later applied to all design scenarios.

Table 3
Average delay and LOS scheme for the S2 roundabout.

Hour	Weekday								Weekend							
	L1		L2		L3		Overall		L1		L2		L3		Overall	
	Delay (s/veh)	LOS	Delay (s/veh)	LOS	Delay (s/veh)	LOS	Delay (s/veh)	LOS	Delay (s/veh)	LOS	Delay (s/veh)	LOS	Delay (s/veh)	LOS	Delay (s/veh)	LOS
6 a.m.	3.9	A	3.7	A	3.6	A	3.8	A	3.9	A	3.6	A	3.7	A	3.8	A
7 a.m.	5.1	A	4.0	A	4.0	A	4.7	A	3.9	A	3.7	A	3.7	A	3.8	A
8 a.m.	9.6	A	5.3	A	6.8	A	8.1	A	4.6	A	4.2	A	4.3	A	4.4	A
9 a.m.	7.8	A	5.6	A	6.9	A	7.1	A	6.1	A	5.0	A	5.6	A	5.7	A
10 a.m.	7.4	A	5.6	A	6.4	A	6.7	A	15.5	B	7.4	A	9.4	B	11.6	B
11 a.m.	7.3	A	5.2	A	5.7	A	6.4	A	21.1	C	6.5	A	9.5	A	14.1	B
12 p.m.	7.4	A	5.5	A	6.7	A	6.8	A	12.4	B	5.9	A	8.0	A	9.7	A
1 p.m.	8.1	A	5.5	A	6.5	A	7.1	A	7.2	A	5.1	A	7.3	A	7.0	A
2 p.m.	7.2	A	5.5	A	6.5	A	6.7	A	8.3	A	5.8	A	9.5	A	8.6	A
3 p.m.	6.9	A	5.6	A	6.4	A	6.5	A	24.0	C	7.4	A	15.4	B	18.4	B
4 p.m.	8.1	A	5.7	A	6.8	A	7.2	A	28.1	C	6.7	A	12.1	B	19.1	B
5 p.m.	9.0	A	6.1	A	9.0	A	8.0	A	24.4	C	6.4	A	10.2	B	19.1	B
6 p.m.	11.0	B	8.1	A	9.6	A	9.9	A	31.8	C	7.6	A	11.9	B	21.8	C
7 p.m.	6.0	A	5.2	A	5.9	A	5.8	A	8.6	A	5.0	A	5.7	A	7.1	A
8 p.m.	5.9	A	4.8	A	5.4	A	5.5	A	6.2	A	4.7	A	5.0	A	5.5	A
9 p.m.	5.9	A	4.8	A	5.2	A	5.4	A	5.3	A	4.3	A	4.5	A	4.8	A

3.2.4. *Emissions modeling*

VSP was employed to estimate hot-stabilized CO_2 and NOx emissions produced by road traffic (USEPA, 2002). VSP was calculated in terms of 1 Hz speed, acceleration-deceleration, and road grade (USEPA, 2002) gathered from VISSIM traffic model calibrated previously with traffic and travel time data. VSP values are grouped in 14 modes of engine regime (deceleration, downhill driving, idling, cruising, acceleration, or uphill driving), and then associated to an average CO_2 and NOx emission rate of each mode (USEPA, 2002).

This microscopic emission model has been well recognized and used extensively in emission prediction studies for several vehicle types and engine propulsions, including, light duty gasoline vehicles – LDGVs (Fernandes et al., 2022), light duty diesel vehicles – LDDVs (Fernandes et al., 2022, 2019), hybrid passenger vehicles – HEVs (Dhatrak et al., 2010), LDTs (Coelho et al., 2009), buses (Zhai et al., 2008) and HDTs (Zhang et al., 2015).

A good body of research conducted by the authors has applied VSP to estimate both emissions generated by vehicles at single-lane and two-lane roundabouts, metering roundabouts and turbo-roundabouts (Fernandes & Coelho, 2017; Fernandes et al., 2015, 2017, 2018; Vasconcelos et al., 2014).

To reflect local car fleet compositions, emissions of each layout were calculated by use of assumptions that passenger cars consisted of 49.7% LDGVs, 49.1% LDDVs, 0.6% HEVs and 0.3% electric vehicles (EVs), and all LDTs, transit buses and HDTs are powered by diesel engines (EMISIA, 2022). The adopted values of emission factors (with exception of EVs) were calibrated using real-world data measured by Portable Emission Measurement Systems (Coelho et al., 2009; Fernandes et al., 2022, 2019, 2010; Zhai et al., 2008; Zhang et al., 2015). Since roundabouts are located on flat roads, the effect of slope was neglected.

3.2.5. *Driving volatility*

The instantaneous driving decisions refer to short-term driving decisions to accommodate situational changes during a trip, such as overtaking maneuvers, approach of adjacent vehicles, proximity to pedestrian crossings, pavement conditions or geometric transitions in the road. Volatility in instantaneous driving decisions can be represented by speed, acceleration, deceleration and vehicular jerk, i.e., change in marginal rate of acceleration or deceleration (Wang et al., 2015). Vehicular jerk is the first derivative of acceleration or the second derivative of speed (Eq. (1)), being a proper kinematic parameter for capturing drivers' abrupt adjustments in speeds (Wang et al., 2015).

$$j = \frac{d(a)}{d(t)} = \frac{d_2(v)}{d(t)^2} \tag{1}$$

where: j is vehicular jerk (m.s^{-3}), a is acceleration (m.s^{-2}) and v is speed (m.s^{-1}).

3.3. *Scenarios management*

Six different design scenarios were established for the S1 (Fig. 9) and S2 roundabouts (Fig. 10).

1 Baseline scenario reflects the current field conditions of the single-lane roundabouts, and it represents the validated traffic model for weekday and weekend traffic conditions;
2 Alternative scenario representing an egg turbo roundabout (in essence a reduced form of the basic turbo-roundabout layout) compliant with Dutch guidelines on turbo roundabouts that includes an entry speed of 40 km.h^{-1} (Fortuijn, 2009a). Because of urban space restrictions, all exits are single lanes. The daily number of U-Turn vehicles from L2 at S1 is lower than 10 so that the geometric design of turbo-roundabout does not allow U-Turn movements from that approach. At the S2 site, the alternative scenario consists of a basic turbo roundabout layout that allows U-Turn movements from all approaches. This is explained by the moderate number of daily U-Turn movements from L2 (50–80 vehicles, depending on the day);
3 Alternative scenario representing a yield controlled RCUT configuration with a direct left turn from L1 approach and two U-Turn crossovers. The main guidelines for three-legged RCUT intersections (Holzem et al., 2015; Hummer et al., 2014) were adopted, namely: (i) distance from the main intersection to the U-Turn crossovers of 120 m (d, as shown in Fig. 1); (ii) design speed of left-turn and U-Turn crossovers set at 20 km.h^{-1}; and (iii) median width higher than 10 m to accommodate the turning radius and width of larger vehicles at U-Turn crossovers. Due to land use restrictions, single-lane left- and U-Turn crossovers were adopted. The length of storage lanes leading to U-Turn and left-turning crossovers was set at approximately 65 m. Concerning the crossing for pedestrians and cyclists, one mid-block crossing at L3 approach was used. To reduce the out-of-direction travel for pedestrians and cyclists, a second mid-block at L1, just beyond the U-Turn crossover, was implemented (Hummer et al., 2014);

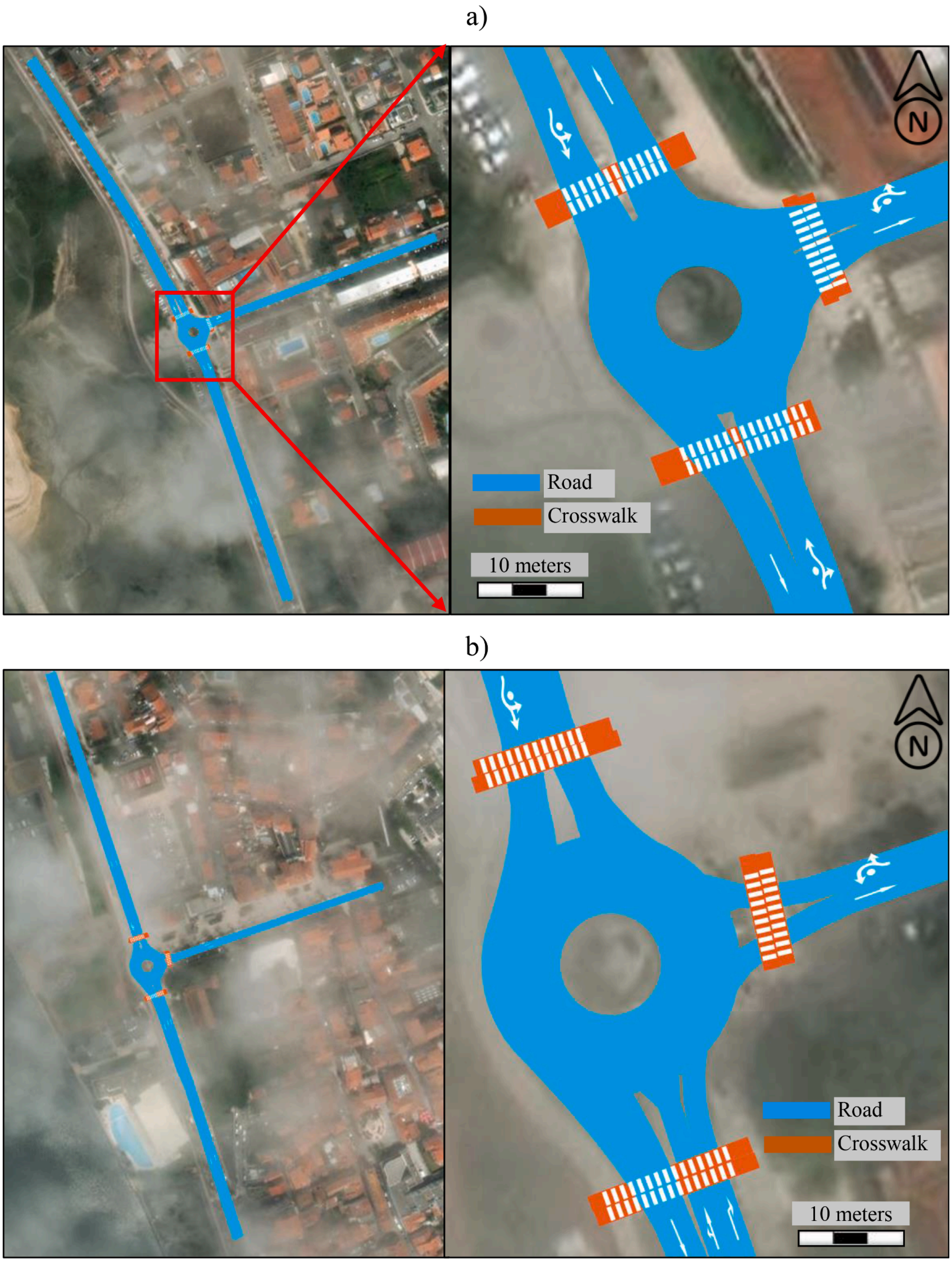

Fig. 7. VISSIM models for the studied single-lane roundabouts: (a) S1 and (b) S2. [Source: Bing Maps]

4 Identical to latter alternative scenario, but L2 approach, left- and U-Turns crossovers are all stop-controlled.

For simplicity, the four above scenarios are referred to as Single-Lane, Turbo-Roundabout, Yield-RCUT, and Stop-RCUT throughout the following sections. Each scenario was modeled using the optimal driving behavior parameters in Table 4.

The traffic performance and emissions indicators were examined on three levels: (a) intersection; (b) approach; and (c) weekday/weekend. The intersection influence area was equal to 250 m in all scenarios. Average travel time, average delay, total time spent in idling, maximum queue length and average speed were used as indicators of traffic performance; CO_2 and NOx were used as environmental measures; and driving volatility was expressed in terms of speed, acceleration, and vehicular jerk distributions. The selected indicators were computed for motor vehicles along the study domain.

4. Results

4.1. Weekday versus weekend

Table 6 summarizes the results of simulations that were conducted

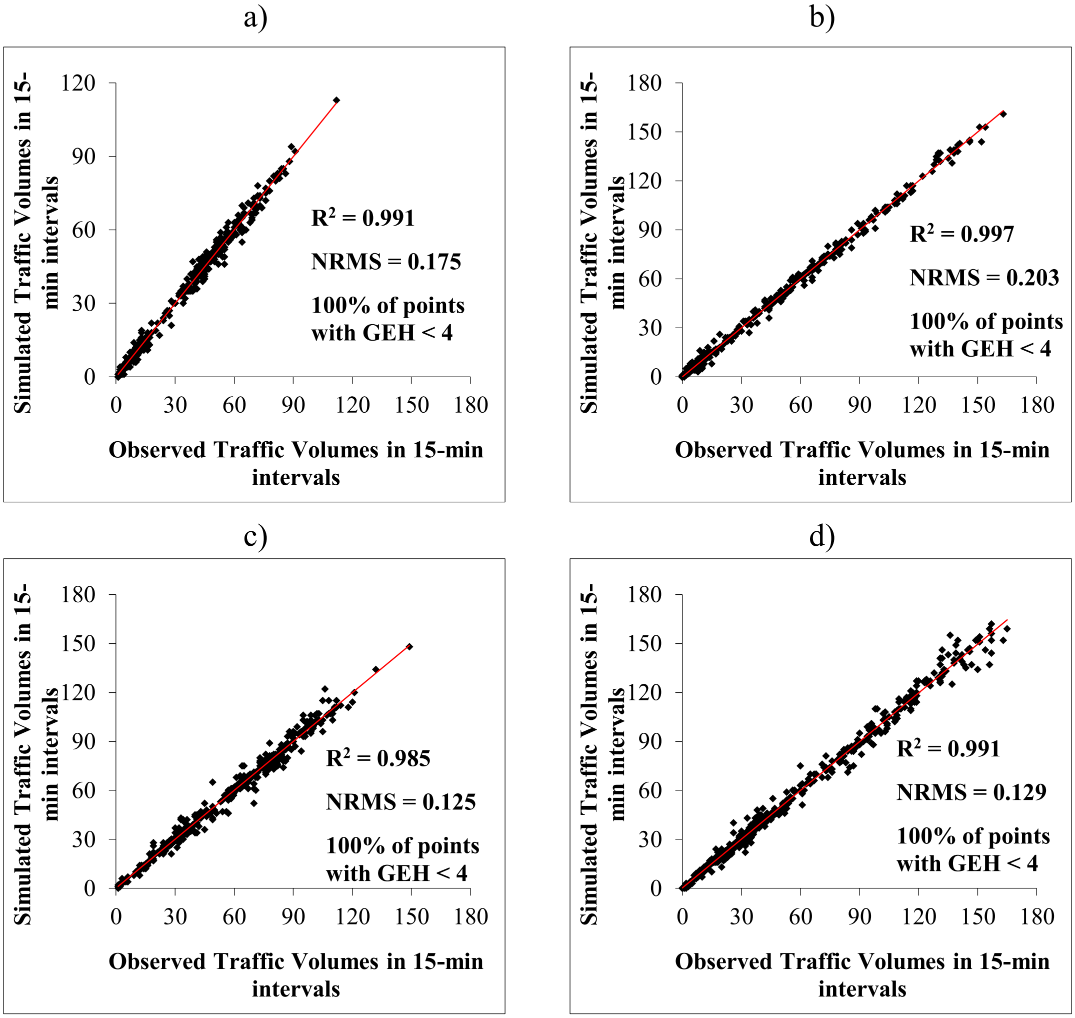

Fig. 8. Summary of model calibration and NRMS and GEH calculations: (a) S1 – Weekday; (b) S1 – Weekend; (c) S2 – Weekday; and (d) S2 – Weekend.

Table 4
Optimal driving behavior of traffic model.

Roundabout	Day	Average standstill distance (m)	Additive part of safety distance	Multiple part of safety distance	Minimum Gap Time (s)	Time before diffusion (s)	Front gap (s)	Rear gap (s)	Lateral distance (m)	Simulation resolution (time steps/ simulation s)
S1	Weekday	0.7	0.9	1.0	3.4	120	0.45	0.45	0.7	10
	Weekend	0.8	0.9	1.0	3.1	120	0.30	0.30	0.7	10
S2	Weekday	0.6	0.8	0.9	3.0	120	0.30	0.30	0.7	10
	Weekend	0.6	0.8	1.0	3.0	120	0.25	0.25	0.7	10

Table 5
Validation results by location and day.

Roundabout	Day	Movement	Field Vehicles	Travel Time (s)	Simulated Vehicles[1]	Travel Time (s)	Relative Difference (%)	Mann-Whitney U	p-value
S1	Weekday	L1-L3	13	57.1 ± 7.9	52	50.5 ± 1.4	+ 13.0%	225.5	0.064
		L3-L1	13	57.2 ± 8.5	52	50.7 ± 1.3	+ 13.1%	228.5	0.072
	Weekend	L1-L3	8	70.0 ± 15.9	52	62.8 ± 4.7	+ 11.5%	55.0	0.119
		L3-L1	10	70.2 ± 8.9	37	64.9 ± 6.6	+ 8.1%	49.0	0.090
S2	Weekday	L1-L3	13	57.1 ± 7.9	48	53.1 ± 2.3	+ 7.5%	258.0	0.341
		L3-L1	13	57.2 ± 8.5	50	57.6 ± 2.1	- 0.7%	248.0	0.190
	Weekend	L1-L3	7	96.9 ± 29.6	45	109.3 ± 11.5	- 11.4%	140.0	0.639
		L3-L1	7	89.4 ± 17.2	41	77.4 ± 7.4	+ 15.5%	93.0	0.140

[1] Number of vehicles required to yield statistically valid results using the procedure outlined in Federal Highway Administration's (FHWA) traffic analysis toolbox (Dowling et al., 2004)

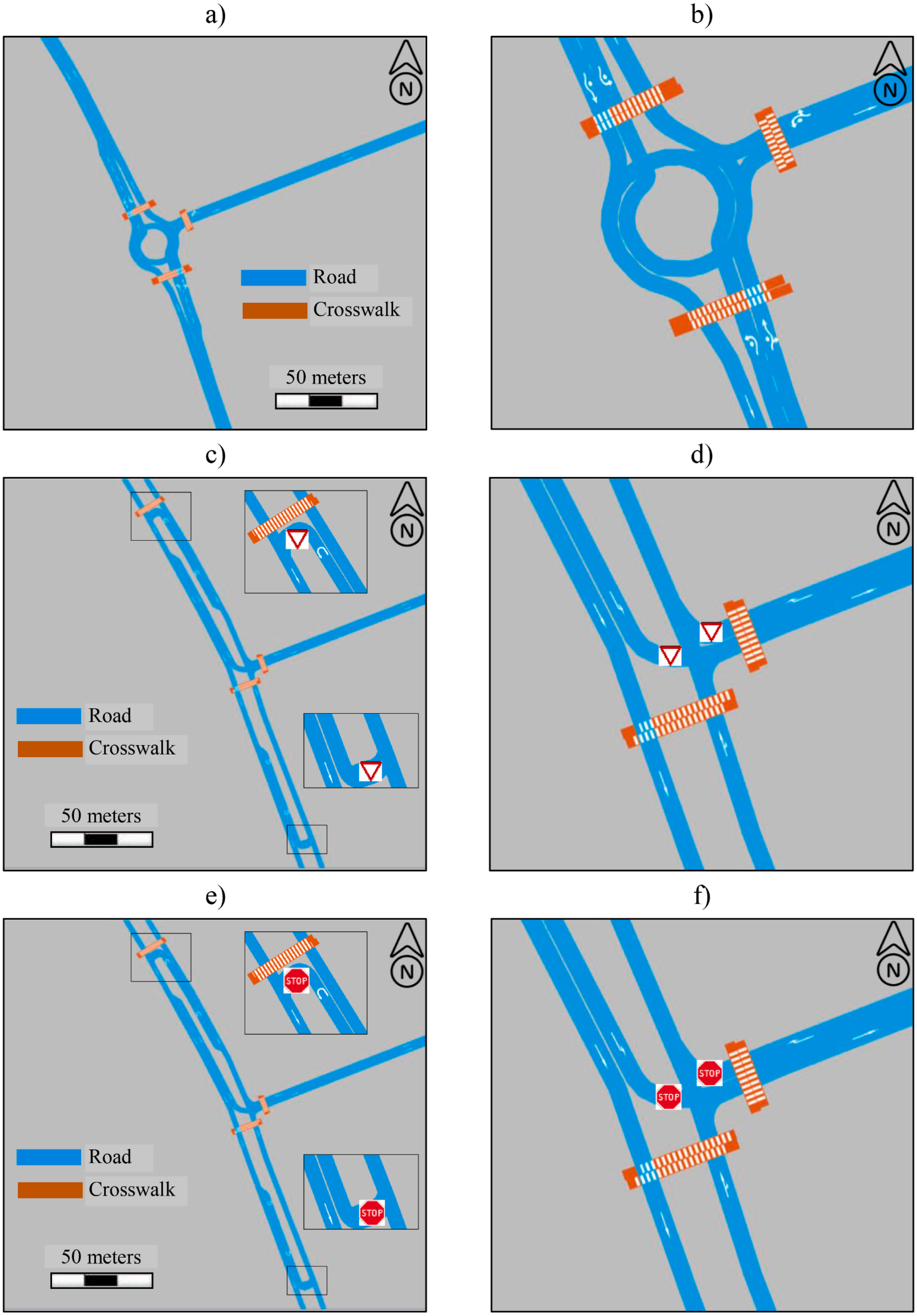

Fig. 9. S1 Design scenarios: (a) Scenario 2 – Corridor area; (b) Scenario 2 – Intersection area; (c) Scenario 3 – Corridor area; (d) Scenario 3 – Intersection area; (e) Scenario 4 – Corridor area; and (f) Scenario 4 – Intersection area.

for all the scenarios and sites. A student-t test with a 95% confidence level was used to compare the means of each indicator between alternative and Single-Lane scenarios. The Turbo-Roundabout gave the best results with respect to travel times (-0.4% in relation to the Single-Lane scenario), average delay (-29.8%), and total CO_2 emissions (-1.4%) during the weekday at S1 site. The improved benefits of turbo roundabout over the single lane layout are in line with those observed in previous studies (Pitlova & Kocianova, 2017; Vasconcelos et al., 2014). The Yield-RCUT was more efficient in reducing idling times (-59.8%), queue lengths (-48.9%), total NOx emissions (-0.3%), and CO_2 emissions per unit distance (-3.5%) and improving vehicle speeds (1.6%). Its design benefits the major through movements because of the ability to have perfect progression in both directions of traveling, resulting in fewer deceleration or acceleration episodes, which are relevant for NOx

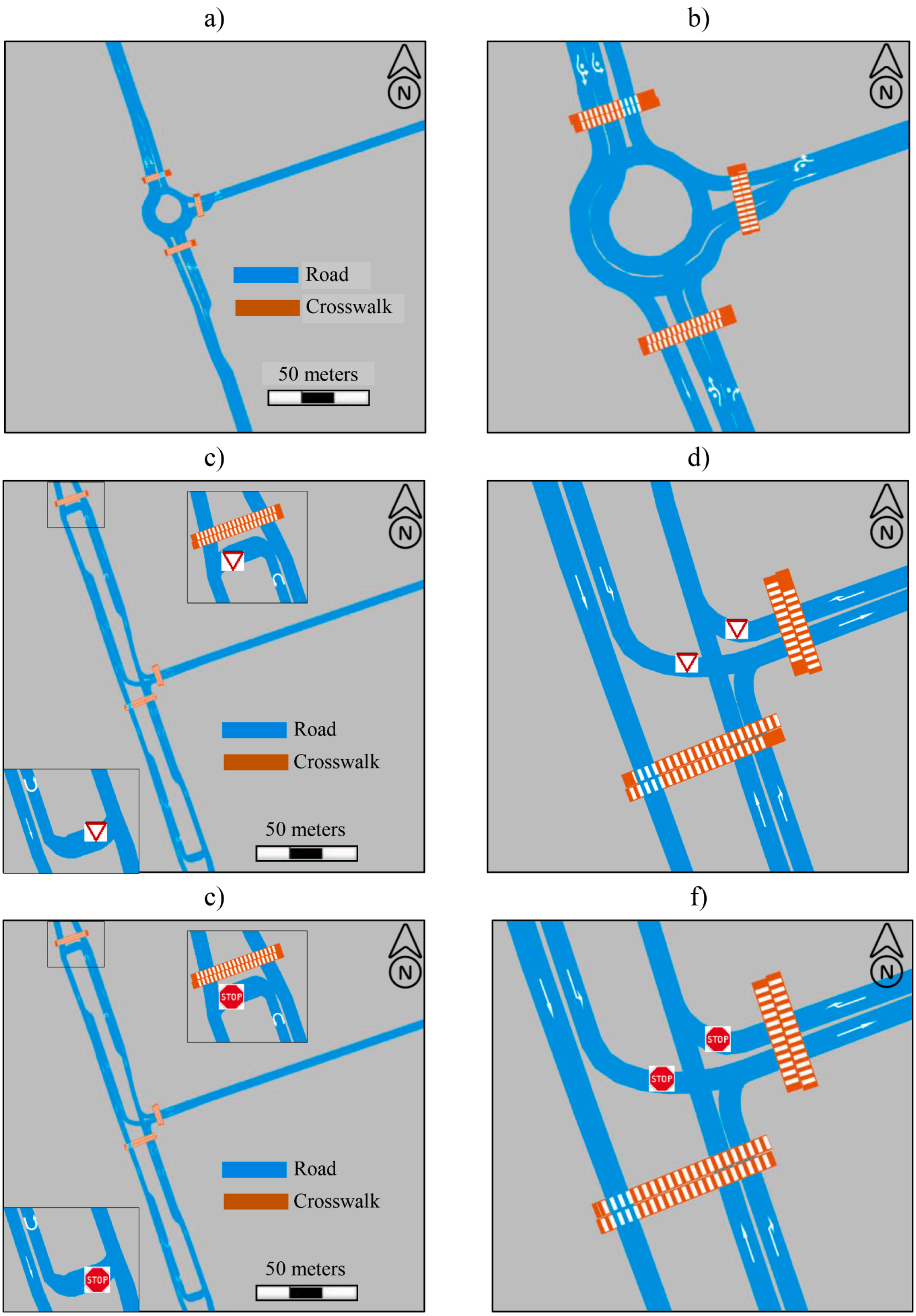

Fig. 10. S2 Design scenarios: (a) Scenario 2 – Corridor area; (b) Scenario 2 – Intersection area; (c) Scenario 3 – Corridor area; (d) Scenario 3 – Intersection area; (e) Scenario 4 – Corridor area; and (f) Scenario 4 – Intersection area.

emissions (Fernandes et al., 2020). The Stop-RCUT had a negative effect on both traffic performance and environmental indicators compared with the Single-Lane scenario.

The Turbo-Roundabout generally surpassed the other intersection scenarios during weekend at S1. This layout achieved average emissions reductions of about 2%, and approximately 63%, 30% and 26% lower idling times, delay, and queue lengths, respectively, as compared with Single-Lane scenario. The Yield-RCUT obtained the shortest queue lengths, and it performed well concerning the reduction of emissions (0.8–1.6%, depending on the pollutant). However, the conversion from single-lane roundabout to Yield-RCUT resulted in 0.6 and 2.3% increases in the average travel time and delay, respectively. The Stop-RCUT was the worst design solution according to both traffic performance and emission indicators.

Table 6
Summary of daily traffic performance and emissions indicators per day and scenario.

Site ID	Day	Scenario	Performance Indicators					Emission Indicators		
			Average travel time (s.veh^{-1})	Total idling time (s)[1]	Average delay (s.veh^{-1})	Average speed (km.h^{-1})	Maximum queue (m)	Total CO_2 (kg)	Total NOx (kg)	Average CO_2 (g.km^{-1})
S1	Weekday	Single-Lane	47.8	1,878	1.2	36.8	20.3	507.9	3.6	149
		Turbo-Roundabout	-0.4%	-57.3%**	-29.8%**	1.1%	-12.7%**	-1.4%	-0.1%	-2.0%
		Yield RCUT	1.5%	-59.8%**	-22.3%**	1.6%	-48.9%**	-0.5%	-0.3%	-3.5%*
		Stop RCUT	4.3%*	823.0%**	105.6%**	-1.3%	-21.2%**	3.0%	3.6%*	-0.1%
	Weekend	Single-Lane	48.4	5,781	1.6	36.7	35.9	678.0	4.7	161
		Turbo-Roundabout	-1.0%	-63.1%**	-29.8%**	1.5%	-26.4%**	-1.8%	-1.5%	-2.3%
		Yield RCUT	0.6%	-20.0%**	2.3%	1.4%	-60.0%**	-0.8%	-1.6%	-3.4%*
		Stop RCUT	2.6%	1,036.3%**	127.3%**	-0.6%	-46.5%**	1.7%	0.9%	-0.9%
S2	Weekday	Single-Lane	52.1	14,022	4.1	32.3	36.4	866.7	7.0	169
		Turbo-Roundabout	-2.3%	-58.3%**	-33.2%**	3.3%	-11.0%**	-4.3%*	-4.0%*	-4.9%**
		Yield RCUT	0.4%	-73.2%**	-39.3%**	4.3%*	-46.5%**	-3.4%*	-1.2%	-7.6%*
		Stop RCUT	6.6%*	548.1%**	33.4%**	-1.8%	-15.0%**	2.7%	7.2%*	-1.7%**
	Weekend	Single-Lane	60.0	116,947	8.0	29.3	70.0	1,269.7	9.1	207
		Turbo-Roundabout	-8.9%**	-60.0%**	-40.4%**	13.2%**	-21.7%**	-9.5%**	-10.0%**	-10.1%**
		Yield RCUT	-7.4%**	-72.1%**	-43.0%**	15.0%**	-54.1%**	-8.9%**	-9.6%**	-11.6%**
		Stop RCUT	-2.7%*	206.7%**	5.1%*	9.5%**	-30.3%**	-4.0%*	-4.1%*	-6.9%**

[1] Number of seconds with motor vehicle travel speeds lower than 5 km.h^{-1}

* p-value < 0.05;

** p-value < 0.001

The findings from S2 indicated that Turbo-Roundabout was the best suited intersection for mitigating emissions impacts (4.3% and 4.0% less CO_2 and NOx, respectively, in comparison with Single-Lane scenario) under weekday conditions. The Yield-RCUT also produced lower amounts of CO_2 (3.4%) and NOx (1.2%) emissions than the existing intersection. The performance results from Yield-RCUT simulations confirmed its superiority over the Single-Lane and Turbo-Roundabout scenarios, with exception of the intersection travel time (0.4% higher than the Single-Lane value). Not only did the Stop-RCUT increase CO_2 (2.7%) and NOx (7.2%) emissions over the Single-Lane scenario, but the Stop-RCUT also increased intersection travel time (6.6%), idling times (548.1%), and average delay (33.4%).

Regarding weekend conditions at S2, the Turbo-Roundabout and the Yield-RCUT behave identically and experienced comparable emissions as reductions were in the order of 10% compared with Single-Lane. Results did not show a consensus about the best performing intersection, i.e., Turbo-Roundabout and Yield-RCUT from a traffic performance point of view. The Stop-RCUT offered advantages in performance indicators, as it manages to reduce travel time and queue lengths by 2.7% and 30.3%, respectively, as opposed to the corresponding values in Single-Lane scenario. Its implementation also allowed emissions savings up to 4% at the S2 site. Despite these benefits, the Stop-RCUT underperformed the Turbo-Roundabout and the Yield-RCUT during a typical weekend.

The analysis of statistical tests of Table 6 revealed that the differences in total idling time, average delay, and maximum queue length between Turbo-Roundabout and Single-Lane scenarios, and Yield-RCUT and Single-Lane scenarios were statistically significant with p-value $<$ 0.05 in most of traffic conditions. The differences between alternative and Single-Lane scenarios were statistically significant at 95% confidence level in all indicators during the weekend traffic condition at the S2 site. The above results confirm our research hypothesis regarding the emissions benefits of certain RCUT designs, and therefore, they can be applied to take advantage of the progression benefits through intersections serving urban areas. However, the environmental benefits of converting Single-Lane roundabout into Yield-RCUT was only statistically significant (p-value < 0.001) at the S2 site during weekend.

It must be highlighted that the environmental benefits of Yield-RCUT can be notable in absolute terms. For instance, if one considers the contribution of both days, then the CO_2 would reduce 8 kg and 143 kg at S1 and S2, respectively, after converting the Single-Lane to the Yield-RCUT. The latter intersection type would also mean annual CO_2 and NOx savings of 20,000 kg and 113 kg, respectively, at the S2 site.

Fig. 11 shows the hourly differences (in percentage) of CO_2 emissions between alternative intersection scenarios (Turbo-Roundabout, Yield-RCUT and Stop-RCUT) and the reference (Single-Lane). The emissions benefits of Turbo-Roundabout implementation can be perceived at the S1 during the weekday; 0.1%-2.6% less CO_2, depending on the hour (Fig. 11-a). The CO_2 savings for the Yield-RCUT over the Single-Lane ranged from 0.2% (at 8-9 a.m.) to 2.9% (at 5-6 p.m.). The exceptions were observed at 7-8 a.m., 1-2 p.m., 3-4 p.m. and 9-10 p.m., which may be due to the moderate percentage of U-Turn traffic from L2 approach during these periods. The Stop-RCUT performed worse than Single-Lane roundabout in almost every period.

The Turbo-Roundabout generally promoted positive benefits by boosting a reduction of CO_2 emissions ranging between 0.3% (at 9-10 p.m.) and 7.0% (at 4-5 p.m.) during weekend at the S1 (Fig. 11-b). However, it produced more emissions than did the Single-Lane during the early morning periods (at 6-8 a.m.). These periods are characterized by low traffic volumes ($<$ 100 vph). It was found that benefits of Turbo-Roundabout and Yield-RCUT were less remarkable in the morning than those observed in the afternoon, regardless of the day. The analysis of the hourly impact of the Stop-RCUT showed two distinct behaviors: i) a reduction of CO_2 emissions over afternoon period (2-6 p.m.), which can reach up to 4.8% at 5-6 p.m; and ii) increases were found during the remaining periods that come from small changes (0.1% at 8-9 a.m.) to appreciable differences (6.3% at 6-7 a.m.). These results are explained by moderate pedestrian and cyclist volumes at intersection main crossings during the afternoon period.

The simulations from S2 site showed that Turbo-Roundabout remained consistent at each period, with reductions from 1.5% (at 6-7 a.m.) to 6.6% (at 6-7 p.m.) over the Single-Lane scenario during weekday (Fig. 11-c). The hourly emissions decreased after the implementation of Yield-RCUT as well, except during the 6-7 a.m. and 12-1 p.m. This layout saw a minimal increase in CO_2 emissions time during these two periods, from 0.4 to 0.6%. The Stop-RCUT yielded higher emissions than did Single-Lane in most periods.

The finding revealed that, in a typical weekend at the S2, the use of Turbo-Roundabout and Yield-RCUT reduced the emissions amounts all the time (6 a.m.-10 p.m.) at the S2 site (Fig. 11-d). The differences

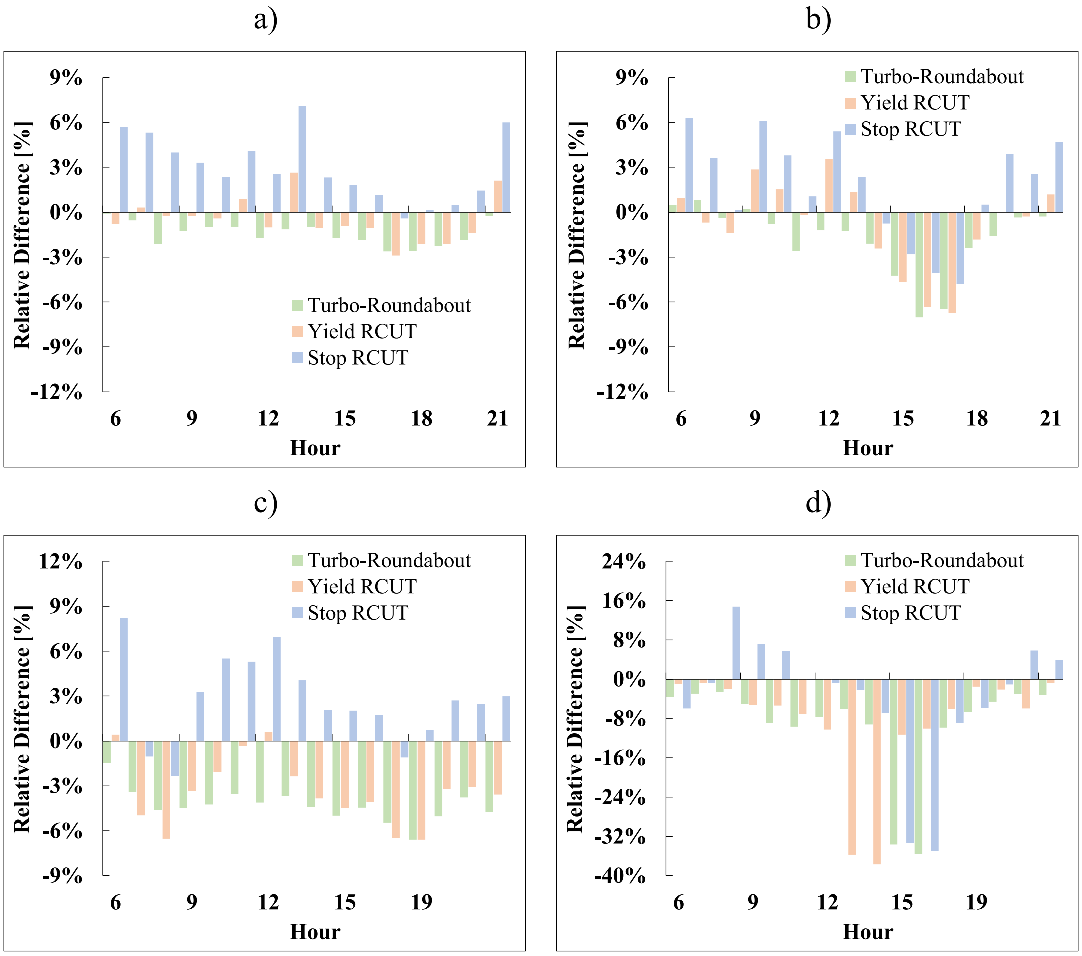

Fig. 11. Variation of hourly CO_2 emissions in relation scenario 1: (a) S1 – Weekday; (b) S1 – Weekend; (c) S2 – Weekday; and (d) S2 – Weekend.

between Turbo-Roundabout and Single-Lane in CO_2 emissions ranged from a 2.6% decrease at 8-9 a.m. to an 35.6% decrease at 5-6 p.m. The Yield-RCUT outperformed the Turbo-Roundabout during the lunch and afternoon periods (at 1-7 p.m.) while Turbo-Roundabout performed better during the morning periods (at 8 a.m.-1 p.m.). The Stop-RCUT had lower emissions than the Single-Lane during the afternoon (at 2-7 p.m.) due to the high demand of motor vehicles, pedestrians, and cyclists together with low percentage of left-turning from L1 and L2 approaches (Section 3.1). The analysis of hourly NOx also resulted in similar findings to those of CO_2 at both locations.

The two-sample Kolmogorov-Sminorv test (K-S test) for 95% and 97.5% confidence levels was applied to determine whether baseline and alternative speed, acceleration, and vehicular jerk cumulative distributions arise from the same population (null hypothesis of test).

Results indicated that less than 40% of data in all scenarios corresponded to speed values below 35 km.h^{-1} at the S1 site (Fig. 12). More than 90% of acceleration and vehicular jerk data were in the range of values from 0 to 0.5 m.s^{-2}, and from 0 to 0.5 m.s^{-3}, respectively. The baseline and alternative cumulative distributions did not follow identical trends, regardless of the driving volatility parameter and day. The two-sample K–S test (D-value) with a 95% confidence level for vehicular jerk during weekday was 0.025 (D-critical = 0.003), 0.096 (D-critical = 0.003) and 0.099 (D-critical = 0.003) for Turbo-Roundabout, Yield-RCUT and Stop-RCUT, respectively. The comparison of Turbo-Roundabout and RCUT, and Yield-RCUT and Stop-RCUT cumulative distributions also rejected the null hypothesis of test.

Approximately 50% of the S2-specific Single-Lane data were in speeds values lower than 30 km.h^{-1} while Turbo-Roundabout and Yield-RCUT had less than 35% of data in the same range of speeds (Fig. 13). The cumulative curves showed that the vehicular jerk values higher than 1.0 m.s^{-3} represented 3.6%, 2.7%, 1.8% and 1.9% of the Single-Lane, Turbo-Roundabout, Yield-RCUT and Stop-RCUT trip times, respectively. The K-S tests confirmed differences between baseline and alternative cumulative distributions for all kinematic parameters. This was especially true for speed data during weekends; the D-values with 97.5% confidence level were, respectively, 0.170 (D-critical = 0.003), 0.183 (D-critical = 0.003) and 0.131 (D-critical = 0.003) for Turbo-Roundabout, Yield-RCUT and Stop-RCUT.

4.2. Major road and street road movements

Table 7 shows the results of S1 and S2 intersections expressed as major road through and left movements, street road left movements and U-Turn movements. For the most important measures of performance (total travel and idling times, and average speed) and emissions (total CO_2 and NOx) results were reported based on the aggregated contribution of the two days.

At the S1 site, the Turbo-Roundabout configuration had a positive effect on traffic performance and emission indicators for all movements, but the major left and street left travel times increased (0.3% and 0.8%, respectively) over the Single-Lane scenario. This can be explained by the design of turbo-roundabout that imposes longer distances, and vehicles may experience longer travel times. The Yield-RCUT scenario outperformed the Single-Lane and Turbo-Roundabout scenarios for the major road through movements; its implementation allowed travel time, idling time, CO_2, and NOx to be reduced by 3.3%, 79.2%, 13.7% and 6.8%, respectively. This RCUT configuration also recorded the highest travel speeds per vehicle among scenarios (3.3%). The Stop-RCUT and

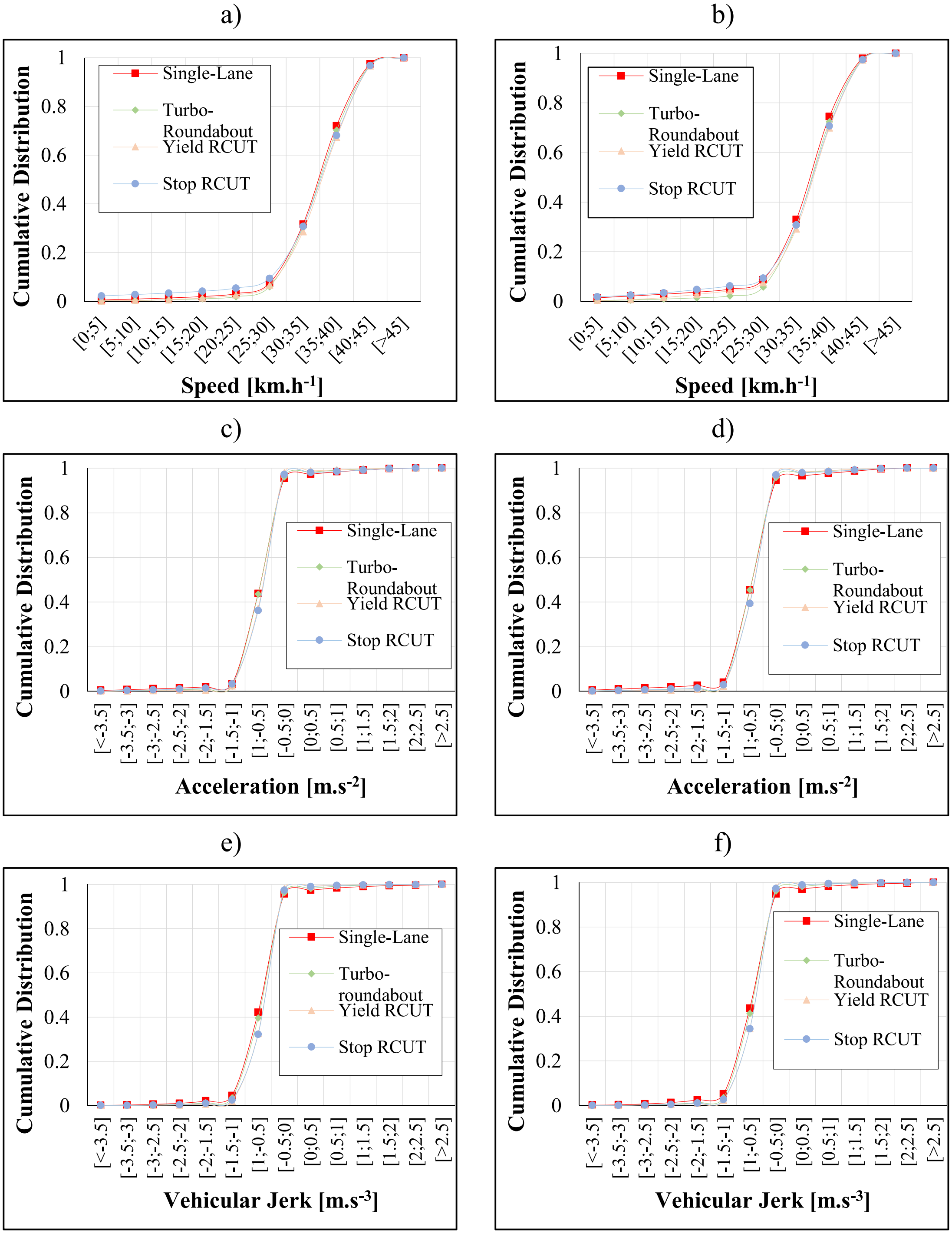

Fig. 12. Analysis of driving volatility indicators in S1: (a) Speed distributions – Weekday; (b) Speed distributions – Weekend; (c) Acceleration distributions – Weekday; (d) Acceleration distributions – Weekend; (e) Vehicular Jerk distributions – Weekday; and (f) Vehicular Jerk distributions – Weekend.

Yield-RCUT scenarios performed identically according to the traffic performance and emission indicators for the major road through movements. The street road left-turn and U-Turn movements were negatively affected by the RCUT (Hummer et al., 2014). By the nature of the design, the street road left and U-Turn turning traffic must travel an additional distance to the downstream U-Turn crossovers. The differences ranged from an 30.7% increase at the U-Turn movement (Yield-RCUT) to an 66.3% increase in CO_2 at the street road left movement (Stop-RCUT), and from an 42.6% increase at the U-Turn movement (Yield-RCUT) to an 91.2% increase in NOx at the street road left movements (Stop-RCUT).

Regarding the S2 site, it can be seen an improvement in both traffic performance and emission indicators with the adoption of the Yield and Stop-RCUT designs for the major road through movements. The travel time, idling time, CO_2, and NOx savings for these AIDs over the Single-Lane Scenario were approximately 18%, 78%, 24% and 21%, respectively. The Turbo-Roundabout scenario also provided a significant advantage in traffic operations at S2 major road through movements, compared with the Single-Lane scenario (13.8%, 55.8%, 19.0% and 14.5% less travel time, idling time, CO_2, and NOx emissions, respectively). The Yield-RCUT also reduced idling times, CO_2, and NOx by 57.2%, 8.9% and 4.3%, respectively, for the major road left movement.

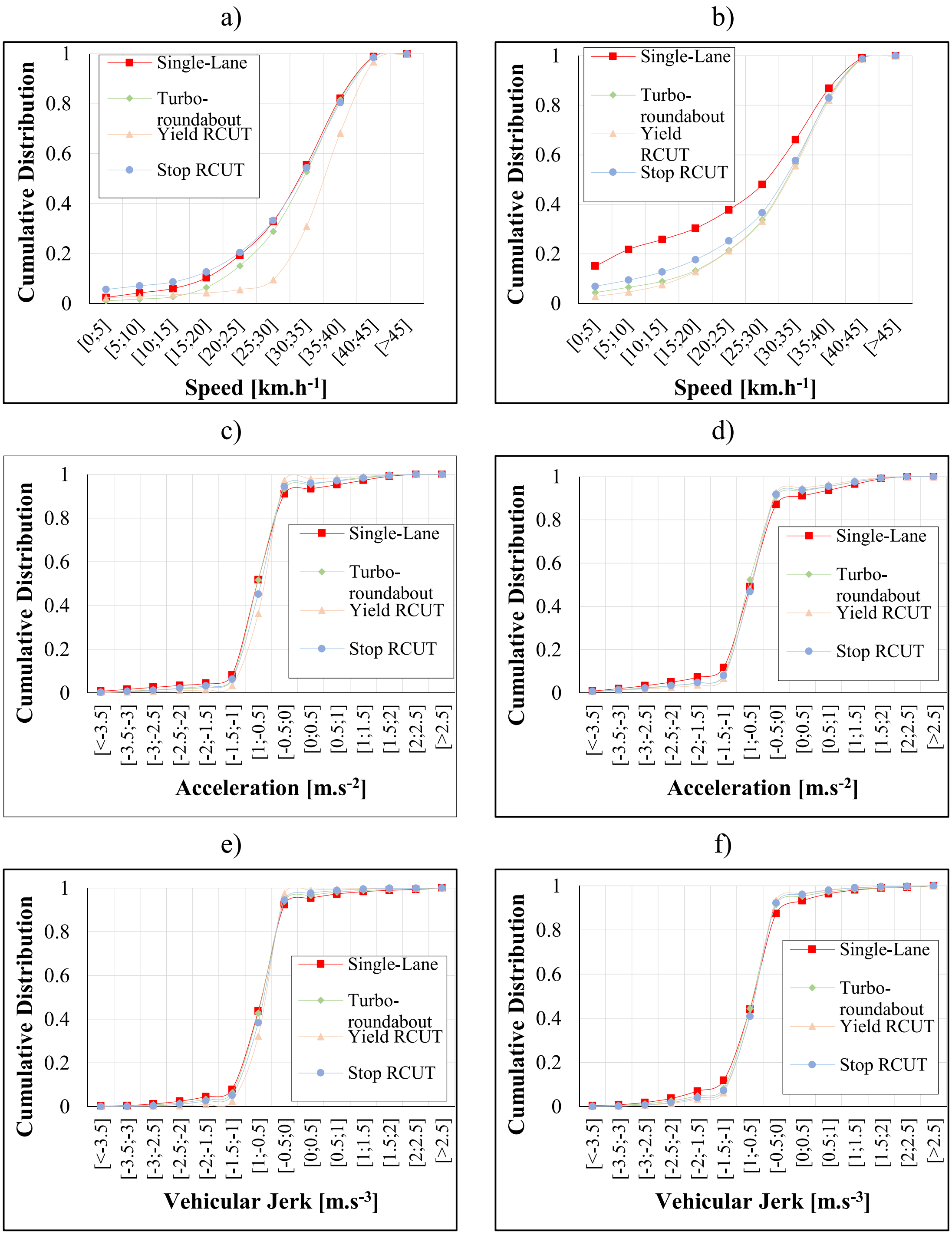

Fig. 13. Analysis of driving volatility indicators in S2: (a) Speed distributions – Weekday; (b) Speed distributions – Weekend; (c) Acceleration distributions – Weekday; (d) Acceleration distributions – Weekend; (e) Vehicular Jerk distributions – Weekday; and (f) Vehicular Jerk distributions – Weekend.

The analysis of street road left, and U-Turn movements showed that the turbo-roundabout achieved the best performance at S2 site. It was the only scenario that decreased CO_2 (5.3% and 14.7%, depending on the movement) and NOx (0.1% and 10.8%, depending on the movement), compared with the Single-Lane scenario. At the Yield-RCUT, the major road left, and street road left movements were affected differently. The major road left movement improved all indicators (3.0% higher average speeds, and 5.6%, 57.2%, 8.9% and 4.3% less travel time, idling time, $CO_{2,}$ and NOx, respectively) while street road left movements were affected negatively, with increases from 43.2% to 54.7% (depending on the indicator) over the Single-lane roundabout values. The Stop-RCUT gave the worst results for street road left movement, as it increased travel times, CO_2, and NOx by 85.5%, 74.0% and 89.7%, respectively.

Apart from U-Turn movements, the replacement of Single-Lane roundabout by a Turbo-Roundabout did not result in statistically significant differences in total NOx (p-value $>$ 0.05) in the remaining movements (Table 7). The differences in total travel and idling times, and total CO_2 and NOx between Yield-RCUT and Single-Lane scenarios were statistically significant with p-value $<$ 0.05, regardless of the site and movement. Most of the movements and indicators exhibited statistically significant differences between the Stop-RCUT and Single-Lane scenarios. The exceptions were in the total travel time and average speed

Table 7
Summary of traffic performance and emissions indicators per movement roads.

Site ID	Movement	Scenario	Performance Indicators			Emission Indicators	
			Total travel time (h)	Total idling time (s)	Average Speed (km.h^{-1})	Total CO_2 (kg)	Total NOx (kg)
S1	Major Road Through	Single-Lane	170.8	4,102	36.9	1,113	7.4
		Turbo-Roundabout	-0.5%	-70.5%**	0.8%	-8.2%**	-0.3%
		Yield RCUT	-3.3%*	-79.2%**	3.1%	-13.7%**	-6.8%**
		Stop RCUT	-3.3%*	-78.3%**	3.0%	-13.6%**	-6.8%**
	Major Road Left	Single-Lane	4.4	284	33.7	27	0.2
		Turbo-Roundabout	0.3%	-94.0%**	3.2%	-5.6%*	-0.4%
		Yield RCUT	-4.2%*	-39.1%**	0.7%	-11.4%**	-5.3%*
		Stop RCUT	10.7%	618.7%**	-12.9%	3.4%*	12.1%**
	Street Road Left	Single-Lane	8.6	495	31.0	52	0.4
		Turbo-Roundabout	0.8%	-31.5%**	-0.1%	-12.6%**	-7.6%**
		Yield RCUT	51.4%**	42.4%**	-2.2%	32.5%**	51.6%**
		Stop RCUT	82.6%**	1,605.8%**	-18.9%**	66.3%**	91.2%**
	All Roads U-Turn	Single-Lane	4.3	146	35.0	29	0.2
		Turbo-Roundabout	-14.7%**	-74.7%**	0.5%	-22.2%**	-17.8%**
		Yield RCUT	45.7%**	116.4%**	-2.6%	30.7%**	42.6%**
		Stop RCUT	62.3%**	1,657.5%**	-15.1%**	44.9%**	59.9%**
S2	Major Road Through	Single-Lane	252.2	60,085	43.0	1584	11.0
		Turbo-Roundabout	-13.8%**	-55.8%**	12.9%**	-19.0%**	-14.5%**
		Yield RCUT	-18.3%**	-78.2%**	17.1%**	-24.0%**	-20.9%**
		Stop RCUT	-18.3%**	-77.9%**	17.1%**	-23.9%**	-20.8%**
	Major Road Left	Single-Lane	30.2	4828	28.8	179	1.3
		Turbo-Roundabout	-3.5%*	-59.6%**	3.2%	-5.7%*	-0.2%
		Yield RCUT	-5.6%*	-57.2%**	3.0%	-8.9%**	-4.3%*
		Stop RCUT	8.7%**	215.7%**	-10.7%*	5.8%*	12.0%**
	Street Road Left	Single-Lane	21.0	1584	26.4	120	0.8
		Turbo-Roundabout	0.3%	0.2%**	-0.7%	-5.3%*	-0.1%
		Yield RCUT	54.1%**	47.3%**	-2.3%	43.2%**	54.7%**
		Stop RCUT	85.5%**	1,342.1%**	-18.9%**	74.0%**	89.7%**
	All Roads U-Turn	Single-Lane	10.9	3,083	28.1	70	0.5
		Turbo-Roundabout	-9.4%**	-75.5%**	7.9%**	-14.6%*	-10.8%**
		Yield RCUT	29.1%**	-58.5%**	0.8%	19.6%*	25.3%**
		Stop RCUT	45.7%**	129.9%**	-5.0%*	32.8%*	40.4%**

[*] p-value < 0.05;
[**] p-value < 0.001

at the major road left movement.

4.3. CO_2 hotspot emission locations

The above results suggest that the relative performance of proposed intersections varies across intersection influence area. Therefore, it is important to understand the segments which are more relevant in the spatial distribution of emissions.

Fig. 14 a-d displays the heatmaps of daily CO_2 emissions per unit segment length on the S1 influence area of Turbo-Roundabout and Yield-RCUT. Analysis of the Turbo-Roundabout weekday data showed that locations with highest values (only 9% of segments), as described by red colors, were found in downstream L3 and upstream L1 (Fig. 14-a). This was 69-219% (depending on the segment) higher than the average CO_2 Turbo-Roundabout influence area value of 356 g.m^{-1}. The percentage of segments with red colors increased during weekend; they contributed to around 37% of the segments in the Turbo-Roundabout influence area in more than 60% of the travel time (Fig. 14-b). The average CO_2 emissions for the Yield-RCUT scenario was about 316 g.m^{-1} (Fig. 14-c) and 373 g.m^{-1} (Fig. 14-d) for the weekday and weekend, respectively. Segments associated with the highest emission values were located along major roads. When the heavy weekend traffic conditions are considered, the proportion of links exhibiting CO_2 values higher than 600 g.m^{-1} accounted for about 45% of the total segments in almost 50% of total extension of the influence area.

At the S2 site, the Turbo-Roundabout hotspot CO_2 locations were found in segments represented by downstream major roads and circulating area (Fig. 15 a-b). The percentage of segments with orange and red colors represented together nearly 63% and 65% of weekday and weekend total segments, respectively. The CO_2 emissions per unit distance in some of these segments were 2-3 times higher than the average intersection values. The segments along L3 exhibited differences in the amounts of CO_2 per unit distance, with lower values in the right-lane than did left-lane. This occurred for two main reasons: i) the left approach lane is used by all through and U-Turn traffic; and ii) the percentage of right-turning is low. The Yield-RCUT had a different distribution in the spatial distribution of emissions between north and south main roads (Fig. 15-c). There were more segments with red colors along L1 area than those observed at L3 area. This may be explained by the high pedestrian and cyclist activity at L1 crossing, leading to more acceleration and deceleration episodes downstream and upstream crosswalk. A detailed view of the weekend data revealed more than 30% of links with CO_2 values above 900 g.m^{-1}; they comprised about 40% and 60% of travel distance and travel time, respectively (Fig. 15-d).

4.4. Impacts of U-turn crossover location

This section evaluated the traffic performance and emissions impacts of changing the location of U-Turn crossovers in relation to the main intersection area (*d*). The focus of the sensitivity analysis was to improve RCUT operation at both sites. Because the Yield-RCUT performed better than the Stop-RCUT design during the weekend, the research team examined several *d* values in the Yield-RCUT based on weekend traffic conditions. Eight distance scenarios were then applied, assuming no changes in the total entry flow at each entry and in the directional split distributions. The testing values ranged from 100 to 170 m with 10 m increments.

Fig. 16 a-d shows the effect of varying the distance from the main intersection to the U-Turn crossovers at the Yield-RCUT on average speed, idling time, and CO_2 and NOx emissions. There were slight differences in average speeds at the S1 site; the values ranged from 36.7 to 37.0 km.h^{-1}. The lowest idling times were observed when the distance

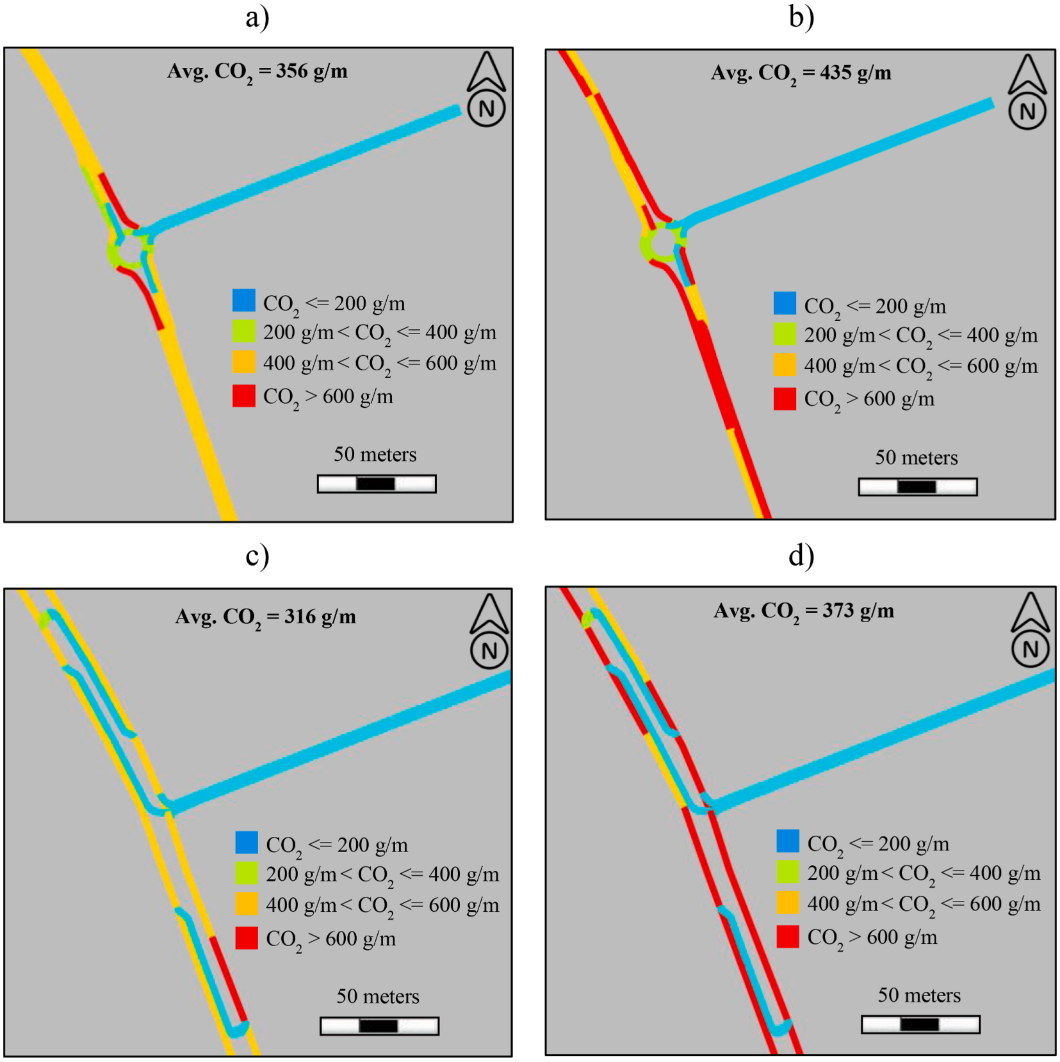

Fig. 14. S1 Spatial Distribution of CO_2 emissions per unit link length: (a) Turbo-Roundabout – Weekday; (b) Turbo-Roundabout – Weekend; (c) Yield-RCUT – Weekday; and (d) Yield-RCUT – Weekday.

values were below 110 m and increased for distances higher than 120 m. After that, the values tend to be relatively stable between 120 and 170 m. Vehicles generated the lowest emissions at the S1 site by adopting a distance value of 100 m (0.6% less CO_2 and NOx than those obtained with the reference distance of 120 m), but the Yield-RCUT underperformed the Turbo-roundabout scenario. The use of smaller distances did not improve traffic operations at the S2, which is line with RCUT guide (Hummer et al., 2014). If one located U-Turn crossovers 100 m from the main intersection, then one would increase idling time, CO_2, and NO_X by 42.3%, 0.3% and 3.4%, respectively, when compared to the existing distance value. This outcome was possibly due to the moderate U-Turn from the L2 street road with destination to left on the L1 major road combined with a higher left-turning traffic at L1, which in turn caused some vehicles to be stopped longer at the storage bay leading to the U-Turn crossover. For instance, the number of vehicles from L2 to the U-Turn crossover at the S2 is on average 2.5 times higher than those observed at the S1 (respectively, 627 and 247 vehicles). The strategy of locating U-Turn crossovers far from the S2 main intersection (170 m of distance) increased CO_2 and NOx increased by 1.5% and 5.2%, respectively, as compared with the existing conditions (120 m).

The main conclusion of this section is that the Yield-RCUT generally performs better than the Single-Lane Scenario, regardless of the location of the U-Turn crossovers in the range of testing values. The use of longer distances decreases the overall performance of the Yield-RCUT while the adoption of shorter distances, i.e., below the minimum values recommended by the FHWA (Hummer et al., 2014), allows some marginal improvements in both traffic performance and emissions indicators. However, a decision maker should carefully examine the circumstances under which the number of right-turning movements from street road to the left major road together to traffic at major roads are relevant because shorter distances may be not enough to provide a storage bay without queue.

5. Conclusions and future research

This research aimed to understand the operational and emission effects of turbo-roundabout and RCUT design compared with single-lane roundabouts installed at urban roads. The research team calibrated traffic, pedestrian, and cyclists demand data of two existing three-leg single-lane roundabouts over a two-day period VISSIM. After that, they compared the results with equivalent yield- and stop-controlled RCUT and turbo-roundabout designs. The VSP emission method was employed to estimate emissions produced by each alternative while speed, acceleration and vehicular jerk cumulative distributions were also used as measures of driving volatility. The performance of RCUT designs was also evaluated by varying the distance from the main intersection to the U-Turn crossovers.

At the intersection level, the turbo-roundabout had the lowest CO_2

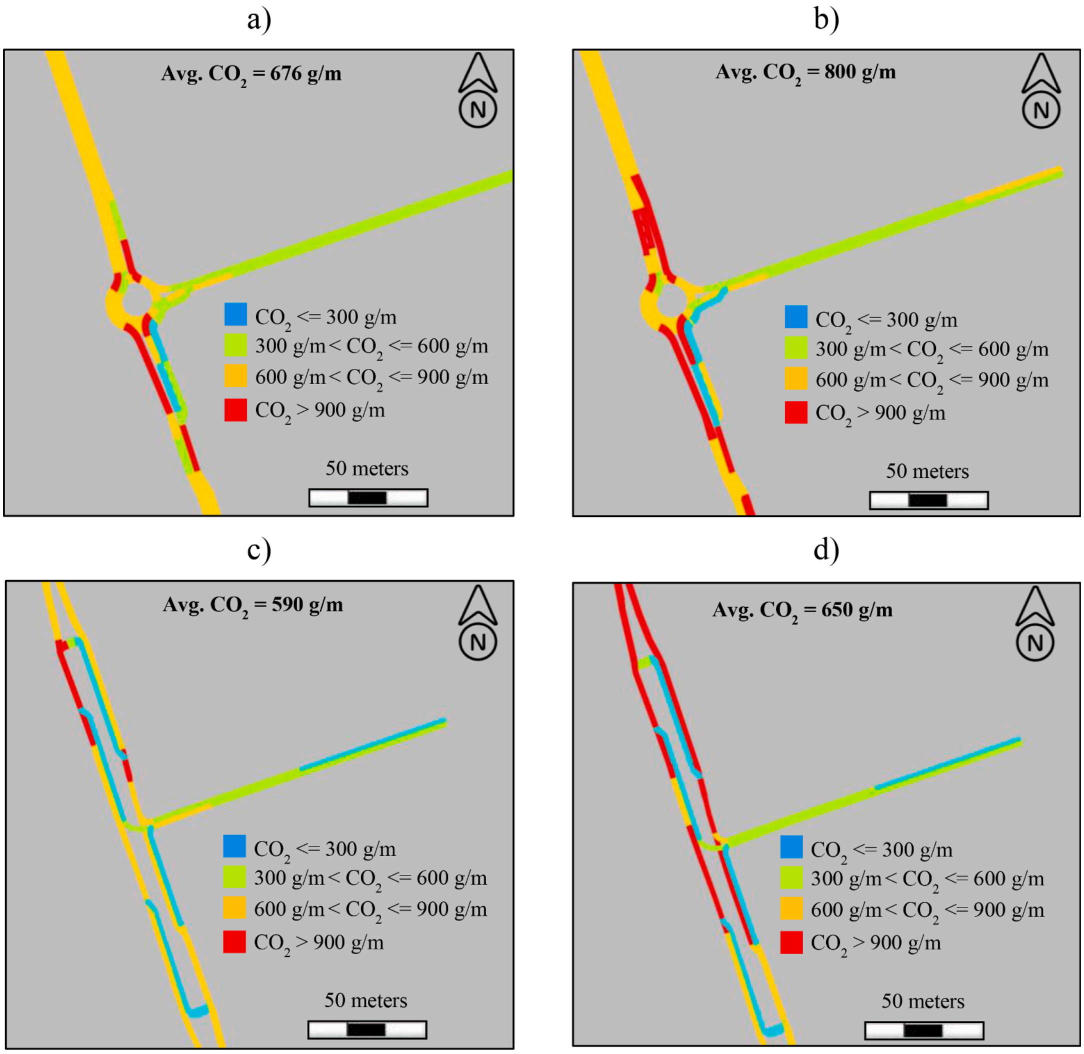

Fig. 15. S2 Spatial Distribution of CO_2 emissions per unit link length: (a) Turbo-Roundabout – Weekday; (b) Turbo-Roundabout – Weekend; (c) Yield-RCUT – Weekday; and (d) Yield-RCUT – Weekday.

emissions and the lowest travel times compared with remaining intersection configurations. It also reduced intersection-specific average delay, idling times, queue lengths, and NOx emissions, while improving intersection traveling speeds. The Yield-RCUT sites performed better than the existing single-lane roundabouts in both sites and days. This RCUT design consistently achieved the lowest idling times and queues, and highest traveling speeds, compared to the other intersections. It also yielded lower daily CO_2 and NOx emissions than did single lane roundabout but required more travel times. The Stop-RCUT generally emitted the highest amount of pollutant emissions at the two sites. The Yield-RCUT produced lower CO_2 emissions than did turbo-roundabout in some periods, primarily due to the high percentage of through traffic and low U-Turn traffic in certain hours of the day.

Upon analyzing the breakdown of impacts per movement, the major road through movements were positively affected by the RCUT configurations, with lower travel times, idling times, and CO_2 and NOx emissions than the single-lane and turbo-roundabout. The turbo-roundabout produced lower emissions than the single-lane roundabout regardless of the location and movement. Both street road left, and U-Turn movements were greatly impacted by the RCUT design, with significant increases in emission values over the single-lane roundabouts. These movements require extra traveling distances to a downstream U-Turn crossover, and in doing so, vehicles spend longer travel times and produce greater amounts of emissions along the intersection influence area. The study also confirmed that single-lane roundabout exhibited higher vehicular jerking values than the turbo-roundabout and RCUT designs.

The overall performance of the Yield-RCUT decreased as the distance from the main intersection and U-Turn crossover increased, but it still showed advantages over the existing intersection in the range of crossover locations (100–170 m). Adopting distance values of 110 m or less provided additional improvements in both traffic performance and emissions, but this outcome did not hold for moderate traffic volumes at street roads because they can create some queue in the storage bay section leading the U-Turn crossover.

Results presented in this study highlight the potential environmental benefits of Yield-RCUT at urban intersections. Although guides recommend implementing superstreets as corridors rather than isolated intersections, local authorities and traffic planners should consider using Yield-RCUT at the studied sites. These intersections should be where low-volume roads meet high-volume arterial roads with relevant percentage of through traffic, and without effects of the downstream and upstream intersections. Implementing a RCUT instead of single-lane roundabout can also save road traffic external costs in long term, especially those related with the impacts with traffic congestion, climate change and other society-related (e.g., NOx or road crashes) costs.

The methods and methodology applied here can be used to evaluate other urban three-leg intersections with characteristics that may favor

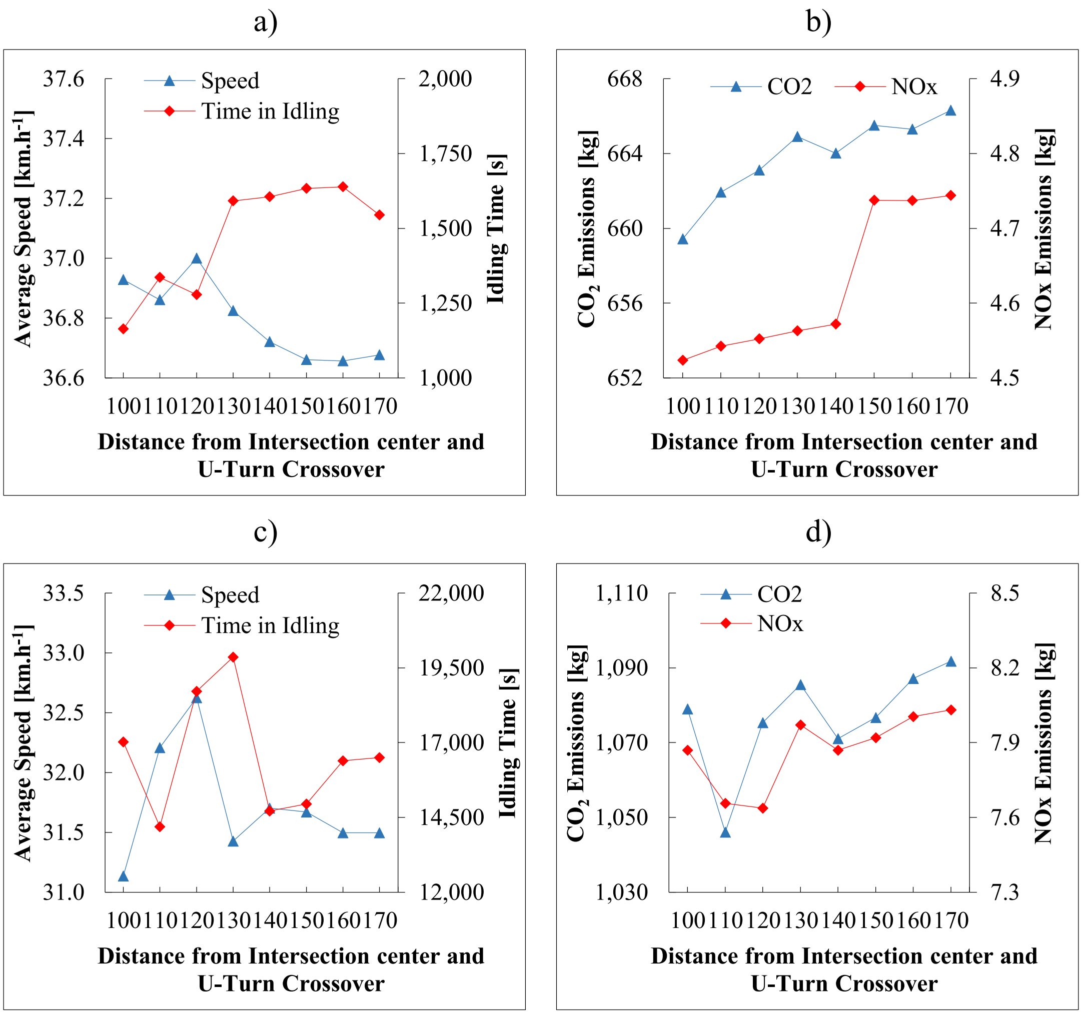

Fig. 16. Traffic performance indicators and emissions versus U-Turn crossover location: (a) Average speed and idling time – S1; (b) CO$_2$ and NOx – S1; (c) Average speed and idling time – S2; and (d) CO$_2$ and NOx – S2.

the implementation of certain alternative design intersections and whose benefits for traffic lack for an integrated impact assessment. It should be highlighted that traffic performance and emissions are not the only parameters that give a complete picture of RCUT operation. Safety of vulnerable road users should also be considered. This is particularly significant at intersections placed along urban corridors where pedestrian and/or cyclist volumes are expected to be relevant.

RCUTs are flexible with crossover locations and storage bays along the corridor as the major roads basically act as a one-way pair. However, site-specific land use and operational characteristics may suggest other factors that influence the overall performance of RCUT. Therefore, the models should be calibrated to traffic, pedestrian and cyclist demands and turning split distribution data for these sites.

This research was valuable in the context of urban planning and clean infrastructure of intersections since it can help local authorities, and transportation engineers, researchers, and other professionals on how to consider, evaluate and implement urban RCUT designs to account for an environmentally sustainable perspective, but some assumptions were made. These, in turn, yield the following drawbacks of the study:

1 The candidate sites were three-leg intersections, meaning that the results cannot be translated to four-leg intersections;
2 The modeling of RCUT was based on two configuration types (yield- and stop-controlled) with one pedestrian and cyclist accommodation; neither the study examined signalized RCUTs nor other crossing alternatives;
3 The analysis of RCUT was only centered on motor vehicles; impacts on pedestrian and cyclist performance and safety were neglected.

The sensitive analysis of RCUT operation relied on the location of U-Turn crossover; other intersection design features are believed worthy of analysis. For any future research analyzing the performance and environmental impacts, the research team recommends selecting four-leg intersection sites to gain more knowledge about the benefits and limitations of the proposed RCUTs. A comparison between yield and signalized RCUT or other AIDs (e.g., median U-Turn) would also be necessary. The research team also suggests conducting a modeling study about the impacts of different pedestrian and cyclist treatments on RCUT operation. Specific measures of pedestrian and cyclist performance (e.g., average delay, travel time) and safety (e.g., time-to-collision) would allow for a good understanding of the effects of crossing alternatives on these vulnerable road users. There is a need for a detailed analysis of movement, in particular left-turning movements from street roads and U-Turn vehicles. This can be done by testing the impacts of several demands and directional split distributions on most sensitive RCUT locations, including storage bay for both U-Turn and left-turn movements, and minor street roads.

Declaration of Competing Interest

Data availability

Data will be made available on request.

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