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Multi-Criteria Assessment of Crosswalk Location on a Corridor with Roundabouts: Incorporating a Noise Related Criterion

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Abstract

Traffic noise is an important source of environmental stress that can damage human health. This phenomenon may be sensitive nearby roundabouts where noise levels may exceed exposure limits. However, the quantification about noise perceived by pedestrians at influence areas of roundabouts is lacking. This research assessed the characteristics of noise along an urban corridor with two roundabouts. A deeper understanding about the exposure to noise levels perceived by pedestrians is a contribution of the paper. The specific objectives are: 1) to characterize corridor-specific operations in terms of traffic and pedestrian performance, carbon dioxide and nitrogen oxide emissions, and noise; and 2) to explore the differences in the optimal crosswalk locations considering above-related criteria. Traffic and pedestrian volumes, vehicle dynamic and noise data were collected during morning and evening peak periods in the selected site. Traffic and pedestrian performance, and vehicular emissions were evaluated using VISSIM traffic model and Vehicle Specific Power (VSP), respectively. Traffic noise was estimated with a semi-dynamical model and an estimation of the corridor Source Power Level (SPL) was used as a distance-free parameter to be compared with other emissions. Finally, a Genetic Algorithm (GA) was applied to find optimal crosswalk locations. It was found that crosswalks nearby the present location (PC = 33 m) provided a good balance among traffic and pedestrian performance, emissions and noise, regardless of peak period. The inclusion of noise related-criteria resulted in some optimal locations next roundabout exit section (13-23 m) mostly due to low pedestrian volumes in the study locations.

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Keywords: pedestrian; crosswalk; peak-hour; traffic volume; noise level; roundabout corridors; emissions; multi-objective optimization.

Introduction

Road traffic generates noise, which is characterised by relatively varied levels, subjecting people to daily exposures of noise phenomenon at different locations. Scientific research has demonstrated that space–time variations in vehicle dynamics due to the roundabouts influence urban soundscapes (Ahac and Dragčević, 2012; Lau et al., 2014). However, site-specific geometrical, operational (e.g., percentage of heavy-duty vehicles) or driving habits may result in some issues in the estimation of noise (Gardziejczyk and Motylewicz, 2016). The available road traffic noise prediction models are typically directed towards the estimation of A-weighted equivalent sound levels (L_{Aeq}) (De Coensel et al.,

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2016). There are numerous studies focused on the analysis of noise in the vicinity of roundabouts either based on theory/simulation (Makarewicz and Golebiewski, 2007; Chevallier et al., 2009; Guarnaccia, 2010; Subramani et al., 2012; Covaciu et al., 2015) or purely empirical (Subramani et al., 2012). Gardziejczyk and Motylewicz (2016) found that the L_{Aeq} values at a signalized roundabout were higher by 3.3-6.7 dBA in comparison to a roundabout. These studies discarded, however, the exposure of pedestrians to traffic noise.
Shen and Wa Tang (2011) showed that 60% of noise levels along major pedestrian sidewalks in Macao exceeded 70 dBA. Cai et al. (2011) used vehicle noise emission and propagation models to study the characteristics of noise near a signal-controlled pedestrian crossing junction. These works neither included a deeper information of pedestrian exposure to noise at the roundabouts nor addressed the design of pedestrian facilities to mitigate noise impacts.

The crosswalk location effects on drivers and pedestrians differed significantly (Silva et al., 2013; Kadali and Vedagiri, 2016; Ong and Mladenovic; 2017). Fernandes et al. (2017) showed that the implementation of crosswalk between closely spaced roundabouts resulted in a trade-off among delay, pollutant emissions and pedestrian safety. Crosswalks near the roundabout exit section increased delay and emissions, especially under high-pedestrian demands, but they represented less injury risks for pedestrians because vehicle drive at slow speeds. However, the study did not include noise criteria in the optimization procedure.

The current research around this topic lacks of solid knowledge about the exposure to noise levels perceived by pedestrians at the roundabout influence areas in different periods of the day. Adequate guidelines for the design of crosswalk that include traffic noise effects are also scarce. The motivation of this study is to integrate vehicle delay, emissions (carbon dioxide - CO_2 and nitrogen oxides - NO_X), and noise criteria in the location of crosswalk between roundabouts. The analysis includes a pedestrian point of view, i.e. pedestrian travel time since crosswalks near mid-block may require long crossing distances. The paper seeks to fill a gap in the current literature by integrating a well-known microscopic traffic model (VISSIM), emission and noise methodologies, and a Genetic Algorithm (GA) and applied them in a real-world case study. This paper intends to focus on the following research questions:

- How do vehicle delay, emissions, pedestrian travel time and noise levels vary during morning and evening peak periods for different crosswalk locations along the mid-block segment of a roundabout corridor?
- What are the differences in optimal crosswalk locations among above criteria?

2. Methodology

2.1 Site selection

The studied site is an urban corridor in Aveiro (Portugal) with two two-lane roundabouts (RBT1 and RBT2) in an open area, as depicted in Fig. 1. The corridor is 470 m long and the spacing between roundabouts is 150 m. There is an overpassed railway (~30 m) located 200 m south of the city train station. The current location of the pedestrian crosswalk (PC) is 33 m from the RBT1 exit section. The posted speed limit in the study site is 50 km/h. The movements a-b and b-a were selected to study pedestrian travel time because pedestrians use these paths from/to the train station from/to city centre. Other movements were not considered for two main reasons: 1) negligible pedestrian volumes (less than 50 pedestrians per hour - p/h); and 2) they did not directly influence traffic operations at the studied crosswalk. Table 1 lists the characteristics of the site such as central island, traffic data and pedestrian volumes. Traffic flow is moderate and principally composed of car passenger vehicles. The average number of vehicles entering RBT1 and RBT2 is 2,100 and 2,300 vehicles per hour (vph) during the morning and evening peak hours, respectively.

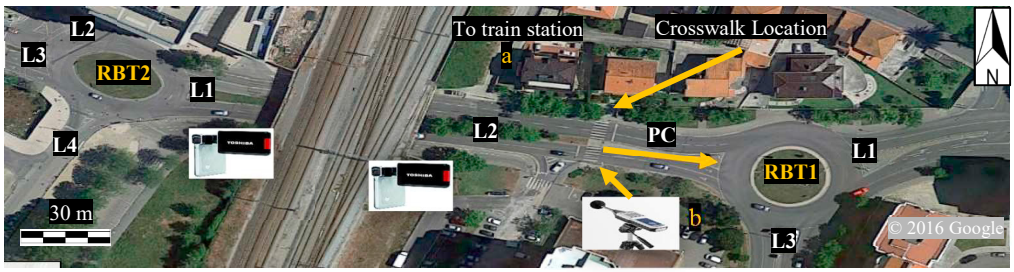


Fig. 1. Aerial view of selected corridor in Aveiro, Portugal, with roundabouts and corresponding legs, PC, and input of pedestrians (a and b).

Table 1. Key Characteristics of Selected Corridor.

Rbt. ID	Central Island [m]	Leg	Morning		Evening		Morning Pedestrian Flow [p/h][a]	Evening Pedestrian Flow [p/h][a]
			Entry Traffic Flow [vph]	Exit Traffic Flow [vph]	Entry Traffic Flow [vph]	Exit Traffic Flow [vph]		
RBT1	41	L1	875	520	640	750	80	90
		L2	560	1,200	1,120	840		
		L3	700	410	530	700		
RBT2	41 and 32[b]	L1	1,225	740	840	1,120		
		L2	80	340	110	420		
		L3	540	750	720	400		
		L4	300	320	490	220		

[a] *Sum of both directions of crossing;* [b] *Oval roundabouts: therefore, there are two values for the inscribed diameter;*

2.2 Monitoring Campaigns

During a typical weekday, traffic counts suggested that morning and evening peak periods occur between 8:00-10:00 a.m. and 5:00-7:00 p.m., respectively. Thus, two sets of traffic, pedestrian, vehicle dynamic and acoustical data were collected on both periods in February 2016. Overhead videos recorded traffic and pedestrian volumes (Fig. 1), and traffic data were compiled to define origin-destination (O-D) matrices for RBT1 and RBT2. The number of train journeys was also gathered from video recordings. The vehicle dynamic data (second-by-second speed and acceleration-deceleration) were recorded using car passenger vehicles equipped with two GPS Travel recorders. More than 30 GPS runs (Fries et al., 2017) for each through movement were performed for this study (~35 km of road coverage). Systematic errors were reduced by using 3 different drivers (two males and one female, ages 26 to 36) who performed an identical number of trips on each monitoring route. These number of runs were sufficient to enable the estimation of a 95% confidence interval. Noise data were carried out using an integrating sound level meter RION-NL52 (see Fig. 1). The tests were followed the ISO 11819-1:1997 standard. The acoustic parameter measured was the L_{Aeq} level. The microphone was in the acoustic field at 1.2 m from the sidewalk and at 7 m from the road axis (two lanes on each direction). The sound pressure levels were recorded every 5 min.

2.3 Traffic and Emissions Modelling

The VISSIM microscopic traffic model was used to simulate site operations (PTV AG, 2011). The model was run for 90 min (8:00-9:30 a.m. and 5:00-6:30 p.m.); the first 30 min were a warm-up period, and data extracted for only during the final 60 min. The following distribution of Portuguese fleet composition was used (EMISIA, 2017): 42% Light Duty Gasoline Vehicles (LDGV), 35% Light Duty Diesel Vehicles (LDDV), and 23% Light Commercial Diesel Vehicles (LCDV). Heavy-duty vehicles and motorcycles were not included in the analysis since they represented 1% of the car fleet. An average pedestrian walking speed value of 1.2 m/s was used (Chandra and Bharti, 2013). The traffic model calibration proceeded in three steps:

1) To determine the minimum number of times to run VISSIM (Fries et al., 2017);
2) To compare observed and estimated traffic and pedestrian volumes, vehicle speeds and acceleration-deceleration rates using model default values;
3) To optimize model parameters using a genetic algorithm (Fernandes et al., 2017) with a calibration target of matching flow rates (Geoffrey E. Havers - GEH must be less than 4 for at least 85% of the links).

Vehicular emissions were estimated based on the concept of vehicle specific power (VSP) for three main reasons: 1) VSP accounts for the effect of different driving modes (acceleration, deceleration, cruise, idling); 2) VSP allows the estimation of instantaneous emissions from second-by-second vehicle dynamics, taking the trajectory files given by VISSIM as input; and 3) VSP includes a wide range of engine displacement values (<2.5 L) (US EPA, 2014) and therefore can be applied to the Portuguese car fleet. VSP is a function of the instantaneous speed, acceleration and deceleration, and slope. Each VSP value is categorized in 14 bins, and an emission factor for each bin is used to estimate the footprint of CO_2 (global pollutant) and NO_X (local pollutant which seriously impacts human health) emissions for LDGV (Fernandes et al., 2016), and LDDV and LCDV (Coelho et al., 2009).

2.4 Noise Assessment

The analysis of noise levels was divided in the following steps: 1) to assess the source power level ($L_{w,i}$) of each vehicle and all traffic flow in each link; 2) to calculate corridor noise levels at a fixed distance; and 3) to evaluate the mean value of the Source Power Level (SPL) of the corridor at the mid-block section between RBT1 and RBT2 (see section 3.2). The source power level of a single car $L_{w,i}$ depends on vehicle speed and running conditions. The procedure implemented by Bandeira et al. (2016) and Guarnaccia (2013) was used to calculate $L_{w,i.}$. Eq. 1 gives the $L_{w,i}$ results for car passenger vehicles:

$$\begin{cases} \alpha + \beta \log v, \text{ if } v > 11.5 \text{ km/h} \\ 82, \text{ if } v < 11.5 \text{ km/h} \end{cases} \tag{1}$$

where: $\alpha = 53.6 \pm 0.3$ dBA; $\beta = 26.8 \pm 0.2$ dBA, results of the fit in (Quartieri et al., 2010).

Once the mean speed data are obtained (by videotape analysis or by VISSIM simulations), the hourly equivalent noise level can be calculated using Eq. 2 (Guarnaccia, 2013; Quartieri et al., 2010):

$$L_{eq}^{1h} = 10 \log N + \alpha + \beta \log v - 20 \log d - 47.563 \tag{2}$$

where: N is the hourly volume; v is the average speed; d is the distance between the road axis and the receiver.

This methodology was validated by comparing measured and estimated noise data in both periods. The simulated traffic flows and speeds for all links at the mid-block area between roundabouts were extracted from VISSIM.

2.5 Design Scenarios and Multi-objective optimization

Baseline scenario is the well-calibrated model with corridor-specific operations. Then, alternative scenarios were applied, assuming possible crosswalk locations (PCs) from 5 to 90 m in 5-m increments (relatively to the RBT1 exit section). Due to the minor street at the L2 of RBT1, the locations between 35 m and 55 m were ignored. For all new crosswalks locations, the research team modelled centroids a and b (Fig. 1) where pedestrians enter and leave the coded network in the same place as the current location. Next, a relationship between PC and vehicle delay, pedestrian travel time, noise, CO_2 and NO_X outputs was established using third-order polynomial regression. The multi-objective procedure incorporated five mathematical functions to perform the following tests: 1) vehicle delay-CO_2-pedestrian travel time; 2) vehicle delay-NO_X-pedestrian travel time; 3) vehicle delay-noise-pedestrian travel time.

As a solution for the problem, the Fast-Non-Dominated Sorting Genetic Algorithm (NSGA-II) is one of the most efficient approaches for solving a wide range of optimization transportation problems (Huang et al., 2010). NSGA-II main strengths are: *i*) diversity in optimal solutions by using crowding distance mechanisms; *ii*) algorithm with low computational requirements; *iii*) storing all non-dominated solutions to guarantee convergence, *iv*) elitist approach since best solutions are saved from one generation to the other; *v*) no need for sharing parameter; and *vi*) possibility of encoding real numbers (Deb et al., 2002). NSGA-II uses an encoding technique for the coding scheme, and then interprets individual chromosomes as optimization variables (delay, CO_2, NO_X, noise and pedestrian travel time). Detailed information about NSGA-II can be found elsewhere (Deb et al., 2002).

3. Results

3.1 Traffic Model Calibration

Fig. 2 exhibits observed and estimated parameters after the calibration procedure. The model used 10 random seed runs which is suitable for urban arterials (Fries et al., 2017). The scatter plots showed that the correlation coefficients between observed and estimated volumes were 0.99 in both demand periods (Fig. 2 a-d). Every link had a GEH value lower than 4 (Holm et al., 2007) which fulfilled the calibration criteria. Albeit good, the fit for speed (Fig. 2 b-e) and acceleration parameters (Fig. 2 c-f) was lower (0.77-0.87 speeds; 0.65-0.68 accelerations) than that obtained for volumes. This happened because VISSIM tend to underestimate acceleration-deceleration values. Noted that reduction speed areas and decision speeds (PTV, 2011) were adjusted to avoid extreme acceleration values in the traffic model.

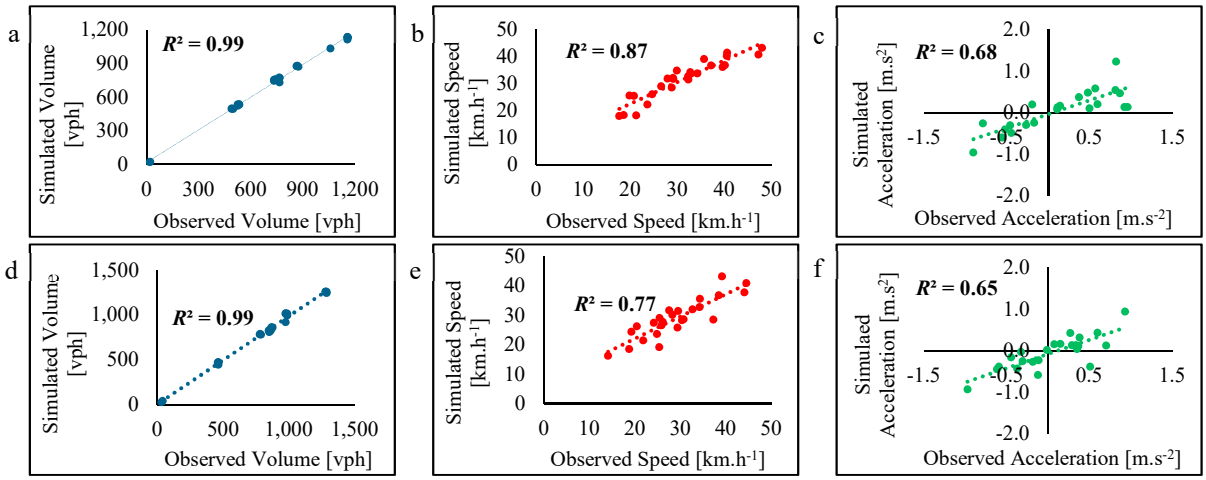
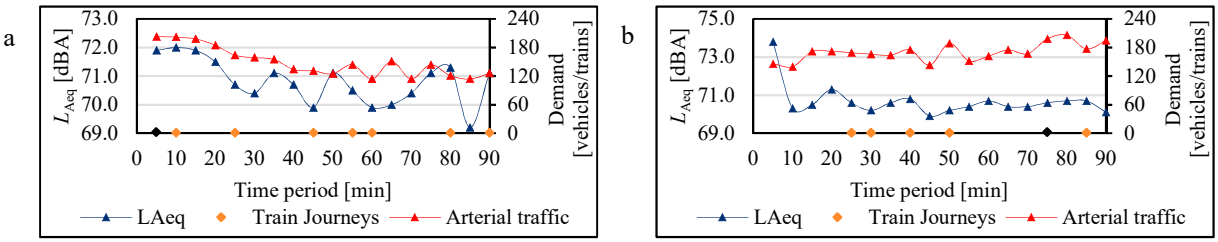


Fig. 2. Observed versus Simulated data: (a) Volumes – Morning peak; (b) Speeds – Morning peak; (c) Acceleration – Morning peak; (d) Volumes – Evening peak; (e) Speeds – Evening peak; (f) Acceleration – Evening peak.

3.2 Noise Model Calibration

The distribution of measured L_{Aeq} and corresponding total arterial traffic over the periods between 8:00-9:30 a.m. and 5:00-6:30 p.m. is illustrated in Fig. 3. Almost 77% and 94% of the samples (18 of 5 min each) reached a L_{Aeq} level higher than 70 dBA during the morning and evening peak periods, respectively. Since arterial flows were roughly constant during each period, L_{Aeq} distributions vary a little from one aggregation period to the other. It was noted that noise values recorded some peaks. The reason for these variations may be due to specific phenomena that affected measurements such as human voices near microphone and crosswalk. The train activity slightly impacted corridor traffic noise (7 to 9 train journeys occurred in the analysed periods).



Note: *orange dots – 1 train; dark dots – 2 trains*

Fig. 3. L_{Aeq} variation near the crosswalk influence area: (a) morning peak period; (b) evening peak period.

As mentioned in the section 2.4, the proposed methodology allows simulating noise at the sound level meter position. Summing up the equivalent noise over each 1 h-simulation period that was produced by the links at the mid-block section between RBT1 and RBT2, an hourly equivalent noise level of about 59 dBA was recorded. The difference between simulated and measured noise levels occurred for three reasons: 1) above-mentioned background noise phenomena; 2) traffic on the South minor road (< 50 vph); and 3) heavy duty vehicles and motorcycles, which are expected to be noisier than passenger cars, were not included in the simulation, since its percentage in the total traffic flow was negligible.

In order to have a general parameter in the PC optimization which does not take into account the position of any receiver, SPL was adopted (Eq. 3), assuming a free flow condition (i.e. almost all vehicles run at the mean speed):

$$SPL = 10\log\left(N \times 10^{\frac{L_{w,i}}{10}}\right) \tag{3}$$

where: *SPL* represents the overall level emitted by cars running in the corridor, in the East or West directions.

Noted that the SPL obtained from Eq. 3 is basically the equivalent noise from Eq. 2 without the propagations terms. If one assumes a given reference distance, then the differences between SPL and propagation terms will give a predicted equivalent level in a range of 60-65 dBA. This results is consistent with field measurements.

3.3 Impacts of crosswalk location on traffic and pedestrian performance, emissions and noise levels

The variation of crosswalk location from 5 to 90 m the RBT1 exit section influenced both vehicles and pedestrians (Fig. 4 a-f). The findings demonstrated that, regardless of demand period, vehicle delay and pollutant emissions were higher for crosswalks placed less than 15 m from the RBT1 exit section. After that, the values tend to be relatively constant. CO_2 and NO_X emissions per unit distance at low PC values were 3% higher than average values recorded at the remaining crosswalks (PC > 15 m) in the morning peak (Fig. 4-a). In turn, pedestrian travel time was nearly constant between 5 m and 65 m, and increased gradually for higher PC values (Fig. 4-b) which confirmed the prior premises. The results of total SPL (combination of through movements) showed that noise levels did not vary for different values of PC (Fig. 4 c). This may be due to fact that any crosswalk location induced congestion in the studied corridor. Accordingly, both traffic flows and average speeds at the mid-block section changed a little.

The analysis of crosswalk locations in the evening period also dictated a similar trend (Fig. 4 d-f). Emissions and traffic delay decreased by more than 5% and 15%, respectively, for crosswalks close to mid-block compared with those next to the limit of the RBT1 circulatory carriageway (PC < 10 m), while pedestrian travel time increased almost 40 sec. This suggests that pedestrians may take certain risk behaviors as crossing outside crosswalk area to decrease time spent from path a to b. Despite traffic demand in the evening peak was slightly high, SPL values were similar among design scenarios (Fig. 4-f).

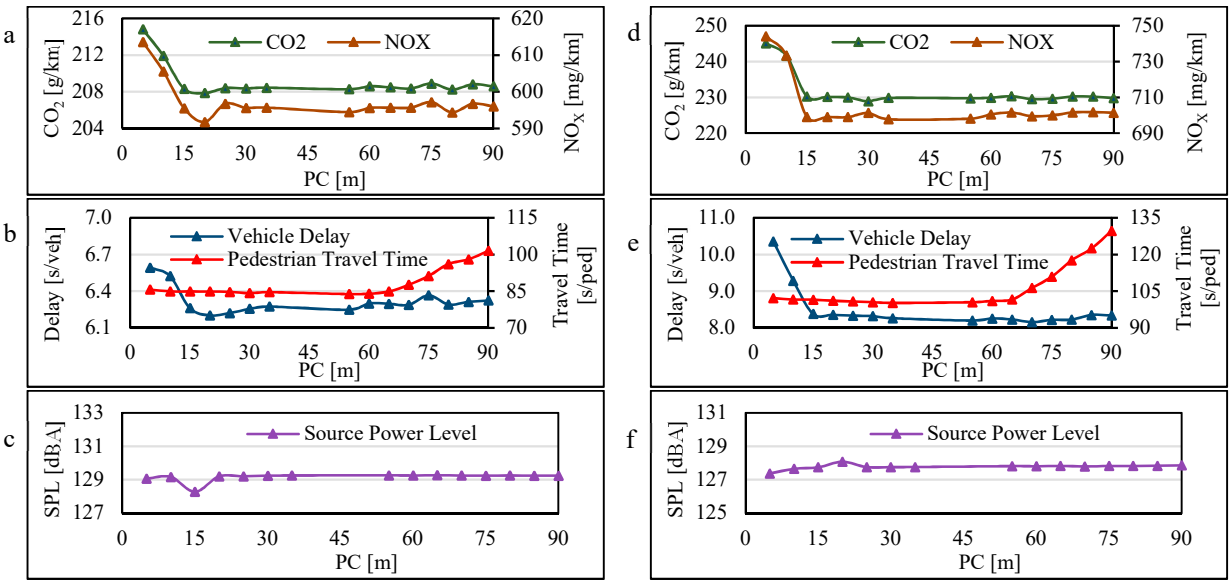


Fig. 4. Impact of crosswalk location on site operations: (a) CO_2/NO_X – morning peak; (b) vehicle delay/pedestrian travel time – morning peak; (c) noise – morning peak; (d) CO_2/NO_X – evening peak; (e) vehicle delay/pedestrian travel time – evening peak; (f) noise – evening peak.

Considering the foregoing discussion, three main conclusions can be drawn: *i*) crosswalks near the roundabout exit section had a negative impact on both traffic delay and vehicular emissions, which agrees with previous research (Fernandes et al., 2017); *ii*) noise levels had small variations, in a range of about 2 dBA, regardless of the crosswalk location and analysis period; *iii*) locating a crosswalk near the midway positions resulted in good traffic and emissions outcomes, however, this fact did not hold for pedestrians (higher travel time).

Once above trade-off was identified, the multi-objective optimization was conducted to improve all outputs simultaneously. The following NSGA-II parameters were used: 8 optimal solutions (population size); 200 generations; 90% and 5% of crossover and mutation rates, respectively. The cubic fit of PC versus each objective variable (R^2 0.68-0.90) showed as reliable since the statistical analysis of R^2 and model coefficients resulted in *p*-values below 0.05

(they did not take 0 value). Repeating this process for above number of generations, NSGA-II gives the optimal PC for the corresponding criteria. Table 2 presents the multi-objective optimization of crosswalk location in both periods. Each PC value is an optimal solution in representative Pareto frontier. The optimal solutions in the morning period were located near the actual crosswalk location (PC = 33 m). This was explained by the lower pedestrian travel time compared to far crosswalks, and concomitantly low CO_2 and NO_X emissions and delay values at those locations. The analysis in evening peak period also confirmed optimal PC between 30 and 34 m away from the RBT1 exit ring. Nevertheless, and by incorporating a noise criteria, optimal solutions were found 13-23 m from the RBT1 exit section and near actual location (30-35 m) in both periods. The reason for this fact is that almost all vehicles were not queueing at the westbound RBT1 and eastbound RBT2 in the morning and evening peak periods, respectively. This resulted in small variations in link-specific vehicle speeds and traffic volumes. For instance, if a decision-maker authority adopts the solution that minimizes noise (PC = 5 m) in the evening peak, then he could increase delay and pedestrian travel time in 24% and 9%, respectively, when compared with existing crosswalk location.

Table 2. Optimal crosswalk locations (PC) of each period considering the traffic and pedestrian performance, emissions and noise criteria.

Period	PC [m]	Delay [s/veh]	CO_2 [g/km]	Ped. Travel time [s/ped]	PC [m]	Delay [s/veh]	NO_X [mg/km]	Ped. Travel time [s/ped]	PC [m]	Delay [s/veh]	SPL [dBA]	Ped. Travel time [s/veh]
Morning	33.8	6.2	207.5	82.2	33.8	6.2	593	82.2	13.1	6.4	128.8	85.2
	33.8	6.2	207.5	82.2	33.8	6.2	593	82.2	13.1	6.4	128.8	85.2
	33.8	6.2	207.5	82.2	34.1	6.2	593	82.2	15.5	6.3	128.8	84.6
	34.3	6.2	207.4	82.2	34.4	6.2	593	82.2	23.1	6.2	129.0	83.1
	34.5	6.2	207.4	82.2	34.7	6.2	593	82.2	30.3	6.2	129.2	82.4
	34.8	6.2	207.4	82.2	34.8	6.2	593	82.2	33.8	6.2	129.3	82.2
	35.0	6.2	207.4	82.2	35.0	6.2	593	82.2	35.0	6.2	129.3	82.2
Evening	32.0	8.1	228.0	97.2	32.8	8.05	694	97.2	5.0	10.0	127.4	105.9
	32.0	8.1	228.0	97.2	32.8	8.05	694	97.2	5.0	10.0	127.4	105.9
	32.3	8.1	228.0	97.2	32.8	8.05	694	97.2	7.0	9.7	127.5	104.8
	32.4	8.1	227.9	97.2	32.8	8.05	694	97.2	9.0	9.5	127.6	103.7
	32.4	8.1	227.9	97.2	32.9	8.05	694	97.2	11.2	9.2	127.7	102.6
	32.9	8.1	227.9	97.2	32.9	8.05	694	97.2	17.4	8.7	127.8	100.2
	33.9	8.0	227.7	97.2	33.2	8.05	694	97.2	35.0	8.0	127.8	97.1

Conclusions

This research focused on the analysis of the influence associated with crosswalk locations between adjacent roundabouts on traffic and pedestrian performance, emissions, and noise levels in morning and evening peaks. The paper also explored the differences in optimal crosswalk locations among above criteria. The findings showed that locating crosswalks near the actual location (PC = 33 m) provided a good balance among traffic (delay) and pedestrian (travel time) performances, and CO_2 and NO_X emissions. Also, the differences in the optimal crosswalk location between global and local pollutant criteria were very small in both demand periods. However, the incorporation of the noise as criteria dictated some optimal locations near roundabout exit section (between 13 and 23 m) mostly because pedestrian volumes were low (< 100 p/h). The analysis results showed that variation in noise levels was very small in the studied periods. Noted that the effect of the roundabout layout (two roundabouts have different shapes) was lower than arterial traffic volumes effects. However, this aspect was beyond the scope of the paper.

This study strives for providing knowledge about the pedestrian exposure to traffic noise, as well as in how to mitigate such phenomenon in the design of crosswalk location. Moreover, the findings of this paper can be tailored to assess other site locations, and lay the ground for a reliable and accurate methodology that includes several indicators. However, some limitations must be noted: 1) although pedestrian travel time provided insight into risk behaviors, the number of times that pedestrians cross outside crosswalks were not considered; 2) limited sample size (one corridor was evaluated); 3) emission estimates only for passenger cars and light commercial vehicles; 4) pedestrian demand effects on optimal crosswalk location were not examined; and 5) deceleration-acceleration effects on noise estimation was not included (only average speeds).

These limitations will be addressed in future research developments. Also, further validation studies should be carried out to check the impact of traffic noise when site-specific operational or geometrical are presented. The improvement of noise methodology could also be done to identify more accurate variations in noise trends. This would allow a better understanding about noise phenomenon in corridors with roundabouts to help practitioners choosing the best design for the pedestrian crossing.

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