MULTI-CRITERIA ASSESSMENT OF CROSSWALK LOCATION IN URBAN ROUNDABOUT CORRIDORS

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ABSTRACT

Mid-block pedestrian crossing areas between closely-spaced roundabouts can have an effect on traffic operations and could result in a trade-off among capacity, environment, and safety. Although research on the impacts of traffic performance on pedestrian crosswalks located at isolated roundabouts has been conducted, very few studies have focused on how traffic operations are impacted by pedestrian crosswalks between adjacent roundabouts in close proximity.

This study examined the integrated effect of a pedestrian crosswalk at different locations between closely-spaced two-lane roundabouts on traffic delay, CO_2 emissions and relative speed between vehicles and pedestrians by using a microsimulation approach. The main purpose of the research was to develop a simulation platform of traffic (VISSIM), emissions (Vehicle Specific Power - VSP) and safety (Surrogate Safety Assessment Methodology - SSAM) in order to optimize such variables. The Fast Non-Dominated Sorting Genetic Algorithm (NSGA-II) was mobilized to identify a set of optimized pedestrian crosswalk locations for the roundabout exit section along the mid-block segment.

The results indicated that locating the crosswalk at 15, 20 and 30 meters from the exit section seemed to be an acceptable solution, providing a good balance among traffic performance, emissions and pedestrians' safety. It was also observed that even at low pedestrian demands, the effectiveness of the crosswalk, in terms of capacity and environment, gradually decreased when located near the circulatory ring delimitation (<10 meters). The findings suggested that crosswalks at mid-block segment (55/60 meters from the exit section) must be also taken into account, especially under high traffic demands.

Keywords: Pedestrians crosswalks, Roundabouts corridors, Microscale modeling, Multi-objective optimization

1. INTRODUCTION AND OBJECTIVES

Roundabouts can provide a safe environment for non-motorized users such as pedestrians and bicycles (*1*). Considering the benefits to pedestrians, roundabouts induce travel at slower speeds, provide shorter crossing distances, and allow pedestrians to only cross one direction of travel at a time (*2*). Operational information, energy and safety impacts of roundabouts are usually collected at isolated intersections. Nevertheless, the impact of roundabouts in corridors is much different. The problem of pedestrian crosswalks on roundabouts capacity may arise in conditions of intense pedestrian or vehicular flows (*2, 3*).

A great deal of research has been conducted in the United States and Europe in the past decades to study the effect of pedestrian crosswalks at isolated roundabouts. In most design manuals, it is suggested that the crosswalks be located 10 to 15 meters downstream of the exit junction in order to avoid affecting the traffic flow in the circulatory ring. However, this range is empirical and supported by few scientific studies (*2, 4-5*). The influence of crosswalks near roundabouts at isolated intersections is usually explored at two levels: capacity/delays and safety.

In terms of capacity, the Highway Capacity Manual (HCM) provides some relationships used to determine the reduction of capacity at roundabouts as a result of the influence of pedestrian streams on traffic. Nonetheless, it does not include the case of a roundabout in close proximity to one or more other roundabouts (*6*). Additionally, several authors developed analytical models addressing the vehicle-pedestrian interaction in roundabouts installed at isolated intersections in the United States (*7, 8*) and Europe (*9*). Concurrently, the use of simulation tools has become widespread for analyzing pedestrian's operations on roundabouts installed at isolated intersections (*3, 10*).

Regarding safety, the assessment of pedestrian accessibility requirements has been the main focus of the current literature. Several studies have demonstrated that roundabouts bring accessibility challenges to pedestrians, especially those who are visually impaired (*11, 12*). As such, there has been an interest in testing different treatments at roundabouts to increase pedestrian safety (*13*). However, these studies did not include the analysis of crosswalks at mid-block areas between adjacent roundabouts.

Albeit extensive, the research on emissions or fuel consumption in roundabouts did not consider the influence of pedestrian crosswalks either at isolated intersections or at a corridor level (*14-17*). Similarly, the few studies that were carried out at roundabout corridors did not examine the influence of pedestrians on traffic operations (*18, 19*). Bak and Kiec (*20*) evaluated the influence of various types of mid-block pedestrian crossing in terms of the overall delay for both vehicles and pedestrians. However, this investigation did not include crosswalks in mid-block segments between adjacent roundabouts.

In summary, the literature review showed that some studies were concerned with the influence of pedestrian crosswalks on the available capacity in isolated roundabouts. Others focused on the accessibility of the crosswalks with the main aim of improving pedestrian's safety. None addressed the influence of mid-block pedestrian crossing between adjacent roundabouts in close proximity on traffic operations, namely, on capacity/delays, vehicular emissions, and pedestrian safety. Basically, the literature lacks a methodology that integrates all the concerns above.

The motivation of this research is to assess the impact of pedestrian crosswalks in roundabout corridors on traffic delay, emissions, and pedestrian safety. Emissions and safety, in conjunction with a multi-objective genetic algorithm, will be used to study the impact of crosswalk locations in a microsimulation platform of traffic. It was hypothesized that the effects of pedestrian crosswalk locations lead to a trade-off analysis among the selected variables. It was expected that, under high traffic and pedestrian demands, a

crosswalk near a roundabout will have a negative impact on emissions and delays and at the same time would be safe for pedestrians, since vehicles drive at slower speeds. In contrast, far crosswalks (close to mid-block) can improve capacity and emissions, but are less safe for pedestrians because vehicles can experience higher speeds at that location.

The present study examines the influence of crosswalks on the different traffic commuters at distinct levels simultaneously, i.e., crosswalk location vs. traffic delay, crosswalk location vs. CO_2 emissions, and crosswalk location vs. pedestrians' safety. This study is also intended to demonstrate that the spacing between roundabouts constrains the pedestrian crosswalk location along the mid-block segment. Therefore the main research questions addressed in this paper are:

- What is the impact of crosswalk location along the mid-block segment of a roundabout corridor with variations in traffic and pedestrian demand on vehicles delay, CO_2 emissions, and pedestrian's safety?
- Considering the same criteria, what are the best locations to build a pedestrian crosswalk in a roundabout corridor?

2. METHODOLOGY

The core idea of the proposed methodology was to develop a microsimulation framework to assess pedestrian crosswalks' impacts on vehicle's delay and emissions, as well as, pedestrian safety. The methodology was divided into five steps. First, data was collected in the study domain (Section 2.2). Then, the network was modelled and evaluated using a microscopic traffic model for the baseline scenario (Section 2.3.1). After that, several scenarios were defined and evaluated (Section 2.4). For each scenario, emissions and safety were evaluated using the VSP methodology and SSAM model (Sections 2.3.2 and 2.3.3, respectively). The steps four and five were related with the calibration/validation of traffic model (Section 2.3.4) and multi-objective procedure, respectively (Sections 2.3.5). Figure 1 illustrates the modelling framework.

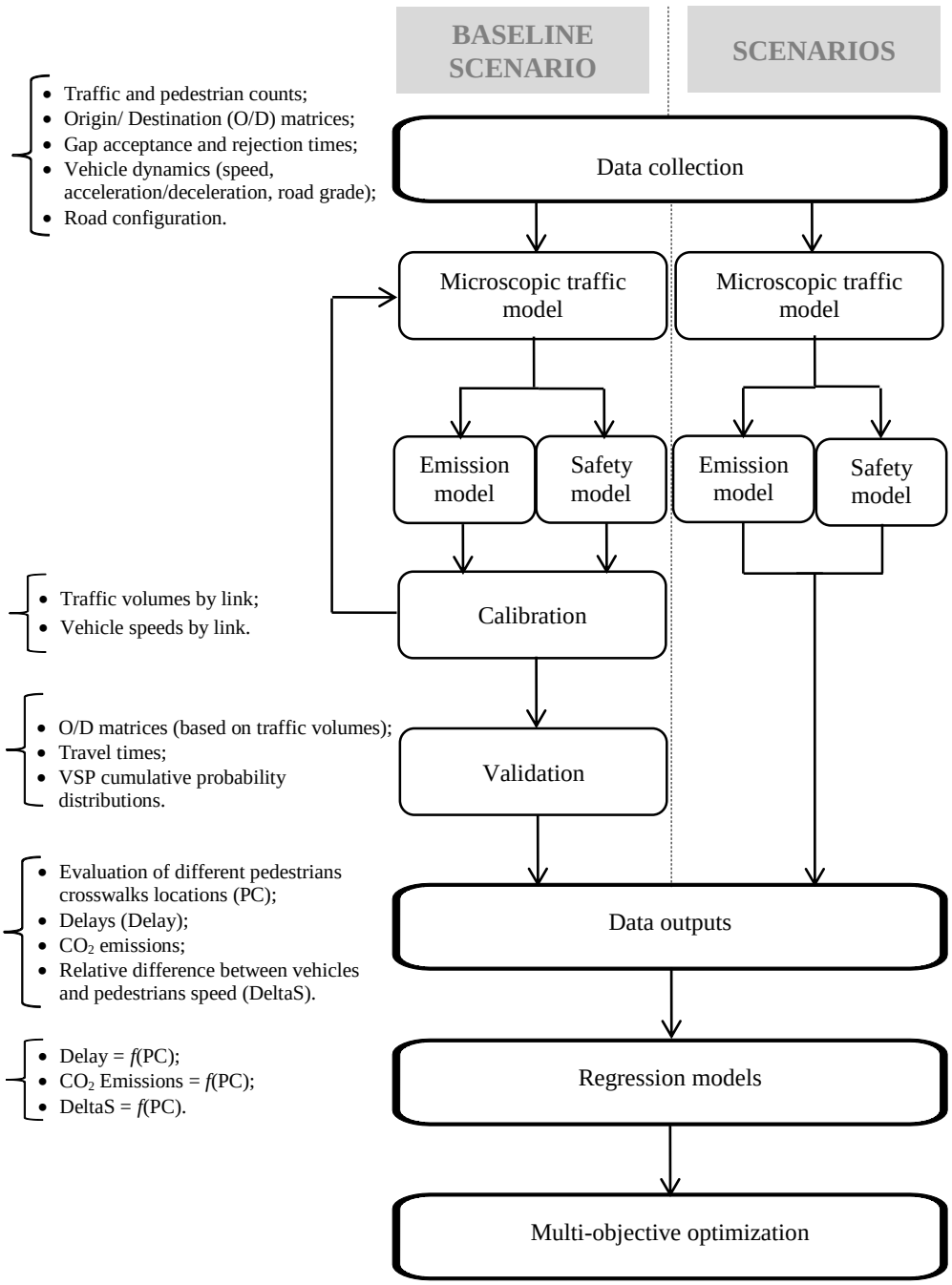

FIGURE 1 Methodological framework.

2.1. Baseline site

The case study consisted of an urban roundabout corridor in the city of Chaves (Portugal), a European medium-sized city with 41,243 inhabitants with a population density of 2,000 inhabitants/km^2 in its downtown area (*21*). As shown in Figure 2, the corridor was 480 meters long (measured from the mid-block of one roundabout to the mid-block of the adjacent roundabout), comprising two two-lane roundabouts, one with three legs (RBT1) and another with five legs (RBT2). The spacing between roundabouts (measured from the upstream yield lanes) is about 150 meters. An arterial with one lane in each direction connects both roundabouts. Due to its central location and roundabout spacing, the arterial has a limited capacity (≈750 vph/pl). The posted speed limit in the study area was 50 km/h.

The actual location of the pedestrian crosswalk is at the upstream end of RBT2. Several explanations have justified this choice: a) higher pedestrian traffic flow (≈ 160 p/h), and b) proximity from the roundabout exit section (≈ 10 meters).

Sites' characteristics such as location, circulating width, inscribed circle diameters and traffic data for each entry and exit legs were summarized in Table 1.

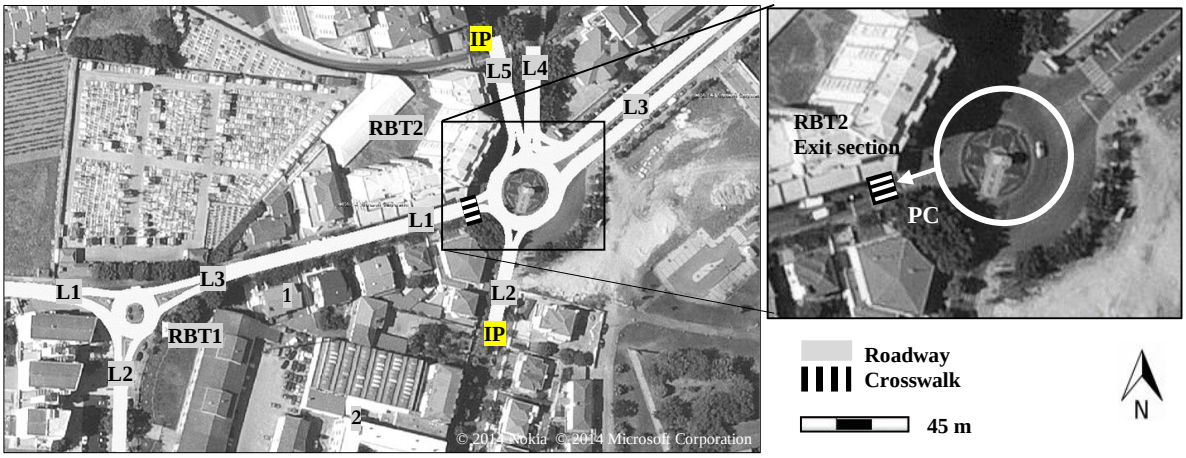

FIGURE 2 Aerial view of the selected corridor with the roundabouts identification (RBT1 and RBT2), legs (L), location of the pedestrian crosswalk (PC) (Chaves, Portugal) and input of pedestrians/centroids (IP).

TABLE 1 Key characteristics of the selected corridor

Roundabout	# circulating lanes	Circulating width [m]	Inscribed circle diameter [m]	Central island [m]	Leg	# approach lanes	Entry traffic [vph] *	Exit traffic [vph] *
RBT1	2	7	16	40	L1	1	457	347
					L2	1	138	187
					L3	1	445	507
RBT2	2	8	41	76	L1	1	509	455
					L2	1	358	285
					L3	2	243	243
					L4	1	130	217
					L5	1	419	547

*During the evening peak periods (4:00 p.m. – 6:00 p.m.)

2.2. Data collection

Traffic and pedestrian volumes, as well as time-dependent Origin-Destination (O/D) matrices, were gathered from two video cameras installed at strategic points in the selected corridor. Time-gap distributions data (gap-acceptance and gap-rejection) for all turning maneuvers was also extracted from the videotapes. Data was collected at evening peak (4:00 p.m. to 6:00 p.m.) during three typical weekdays (Tuesday to Thursday) in February 2014 under dry weather conditions.

For vehicular activity estimation, second-by-second vehicle dynamics data was recorded. A Light Duty Vehicle (LDV) equipped with a GPS Travel recorder was used to perform all feasible movements. 200 GPS travel runs for each movement were extracted and identified for this research (approximately 200 km of road coverage over the course of 12 hours).

2.3. Microsimulation platform for traffic, emissions, and safety

2.3.1. Traffic modelling

VISSIM software package was selected to simulate traffic operations (*22*). VISSIM is widely recognized as a powerful tool for roundabout operational analysis, since it can be calibrated to match deterministic capacity relationships (*3*). It also has been previously used to model pedestrian-vehicle interaction at roundabouts (*10*). VISSIM also allows exporting full disaggregated vehicle and pedestrian trajectory files that can be used by external applications to assess environmental and safety impacts, as described on the following sections.

The simulation model was run for 90 minutes (4:30-6:00 p.m.) with the first 30 minutes used for a warm-up period, and data was extracted only for the remaining 60 minutes. The following distribution fleet composition was considered (*23*): 44.7% of Light Duty Gasoline Vehicles (LDGV), 34.3% of Light Duty Diesel Vehicles (LDDV) and 21.0% of Light Commercial Diesel Vehicles (LCDV). Since remaining categories represented only 1.0% of traffic composition, they were excluded from this analysis. The coded network in VISSIM is depicted in Figure 2. Links volumes (traffic and pedestrians) and speeds were available for all of these links. An average pedestrian walking speed value of 1.2 m/s was adopted (*6*).

2.3.2. CO_2 emissions

To estimate vehicular emissions the VSP methodology was employed (*24*). Several motivations have supported the use of this methodology: a) VSP allows estimating instantaneous emissions based on a second-by-second vehicle's dynamics, taking as input the trajectory files given by VISSIM and b) VSP can be applied to the European car fleet because it includes a wide range of engine displacement values (*24*). VSP is a function of the instantaneous speed, acceleration/deceleration, and the road grade. The VSP values are categorized in 14 modes, and an emission factor for each mode is used to estimate, among others, the CO_2 emissions from LDGV<1.4L (*24*) LDDV<1.9 L (*25*) and LCDV<2.5L (*26*). Previous research has documented the effectiveness of the VSP approach in analyzing emission impacts of different roundabouts' layouts (e.g. *14, 17*). Due to the flat terrain, the effect of the grade was ignored.

2.3.3. Safety

For the safety assessment approach, the software package developed by the Federal Highway Administration - FHWA (Surrogate Safety Assessment Model – SSAM) (*27)* was used, which automates traffic conflict analysis by processing vehicle and pedestrian trajectories (*.trj file) on a second-by-second basis. This approach has all the common advantages of simulation (e.g. safety assessment of new facilities before the occurrence of crashes), but also has some drawbacks: current microscopic traffic models are not able to model some crash types such as sideswipe, head-on or U-turn related collisions (*27*). Vasconcelos et al. (*28*), recognize that despite some limitations regarding the nature of traffic models, SSAM is capable of evaluating the relative safety of different roundabouts layouts.

For each interaction, SSAM stores the trajectories of vehicles (or pedestrians) from the traffic model and records surrogate measures of safety and determines whether or not that interaction satisfies the condition to be deemed a conflict. Time-to-Collision (TTC) was used as a threshold to define if a given vehicle-pedestrian interaction is a conflict; the Relative Speed (DeltaS) was used as a proxy for the crash severity (*27*). TTC is the minimum time-to-collision value observed during the interaction of two vehicles (or

pedestrians) on collision route. If at any time the TTC drops below a given threshold (2 seconds, as suggested for vehicle-pedestrian events (*29*)), the interaction is tagged as a conflict. DeltaS is the difference in vehicles' (or pedestrians) speeds as observed at the instant of the minimum TTC (*27*).

SSAM classifies resulting conflicts into three categories based on a conflict angle (from -180° to +180°). The angle is expressed in the perspective of the first vehicle (or pedestrian), which is arriving at the conflict point, and indicates the direction from which the second vehicle is approaching relatively to the first vehicle (or pedestrian). The type is classified as rear end if 0º < conflict angle < 30°, a crossing conflict if 85º < conflict angle < 180°, or is otherwise a lane change conflict (*27*).

2.3.4. Calibration and Validation

Calibration of VISSIM parameters was made by modifying driver behavior and vehicle performance parameters in the traffic model, and by examining their effect on traffic volumes and speed for each link. The main driver behavior parameters are car-following parameters (average standstill distance, additive and multiple part of safety distance), lane-change parameters, gap acceptance parameters (minimal gap time and minimal headway) and simulation resolution (*22*). To optimize the aforementioned parameters, a procedure based on the Simultaneous Perturbation Stochastic Approximation (SPSA) genetic algorithm was used. The objective function, the minimization of Normalized Root Mean Square (NRMS), is denoted by Eq. (1). The normalization enables the consideration of multiple performance measures, in this case, link volumes and speeds. The calibration procedure was formulated as follows (*30*):

$$\text{Min } NRMS = \frac{1}{\sqrt{N}} \times \sum_{t=1}^{T} \left(W \times \sqrt{\sum_{i=1}^{I} \left(\frac{v_i - \tilde{v}(\theta)_i}{v_i} \right)^2} + (1-W) \times \sqrt{\sum_{i=1}^{I} \left(\frac{s_i - \tilde{s}(\theta)_i}{s_i} \right)^2} \right) \quad (1)$$

Subject to: Lower bound $\leq \theta \leq$ Upper bound

Where:
v_i = Observed link volumes for link *i*;
$\tilde{v}(\theta)_i$ = Estimated link volumes for link *i*;
s_i = Observed speeds for link *i*;
$\tilde{s}(\theta)_i$ = Estimated speeds for link *i*;
N = Total number of links in the coded network;
T = Total number of time periods *t*;
W = Weight used to assign more or less value to volumes or speeds.

Considering the calibration criteria, the current accepted practice, as recommended by the FHWA is to rely on the Geoffrey E. Havers (GEH) statistic for assessing goodness-of-fit. The difference between observed and estimated link volumes (traffic or pedestrians) should be less than 5% for at least 85% of the coded links (*31*).

The model validation was focused on the comparison between estimated and observed O/D matrices and travel times for a preliminary number of runs (between 10 and 20, as suggested by Hale (*32*)). The GEH statistic was also used as a measure of the goodness-of-fit. Along the validation of previous outputs, the observed and estimated Vehicle Specific Power (VSP) cumulative probability distributions were also compared. This validation step allowed assessing the differences in the acceleration/deceleration

profiles between field measurements and simulation. Crash data records were not available in the studied location. Thus, the validation procedure did not include any comparison between conflicts from SSAM and crash data. About 80% of the data was used for calibration and the remaining data for validation.

2.3.5. Multi-objective optimization

The Fast Non-Dominated Sorting Genetic Algorithm (NSGA-II) was adopted in this research (*33*). Several motivations have justified its use: a) diversity in optimal solutions by incorporating the crowding distance into the fitness function and b) a binary tournament approach that accommodates the selection process (*33*). NSGA-II has been reported as an effective algorithm to find a good approximation of an optimal Pareto front (*34*).

Figure 3 displays the NSGA-II main steps, which was implemented in Matlab. A user pre-specified maximum number of generations was defined as the stopping (convergence) criteria of the NSGA-II procedure. Multi-objective optimization results must ensure both the convergence to Pareto Optimal Front (POF) and the diversity of the solutions (*34*). The convergence to POF is based on the comparison among the sets of non-dominated solutions from various generations. The convergence is better if the number of dominated solutions is smaller. The diversity of the solutions is measured by the Spread and the Uniformity Measure metrics estimation (*35*). For purpose of analysis, the delay, the CO_2, and the DeltaS variables are considered to have the same weight during the optimization procedure.

Initially, the maximum number of generations was set to 2000 for all the test instances, while the crossover and mutation rates were set at 90% and 10%, respectively. Each scenario was then run 10 times in the NSGA-II code. For each repetition, the outputs concerning the number of dominated solutions, Spread and Uniformity Measure, were computed. Once the convergence to POF was guaranteed and diversity of the solutions in all scenarios was accomplished, an equal maximum number of generations was used.

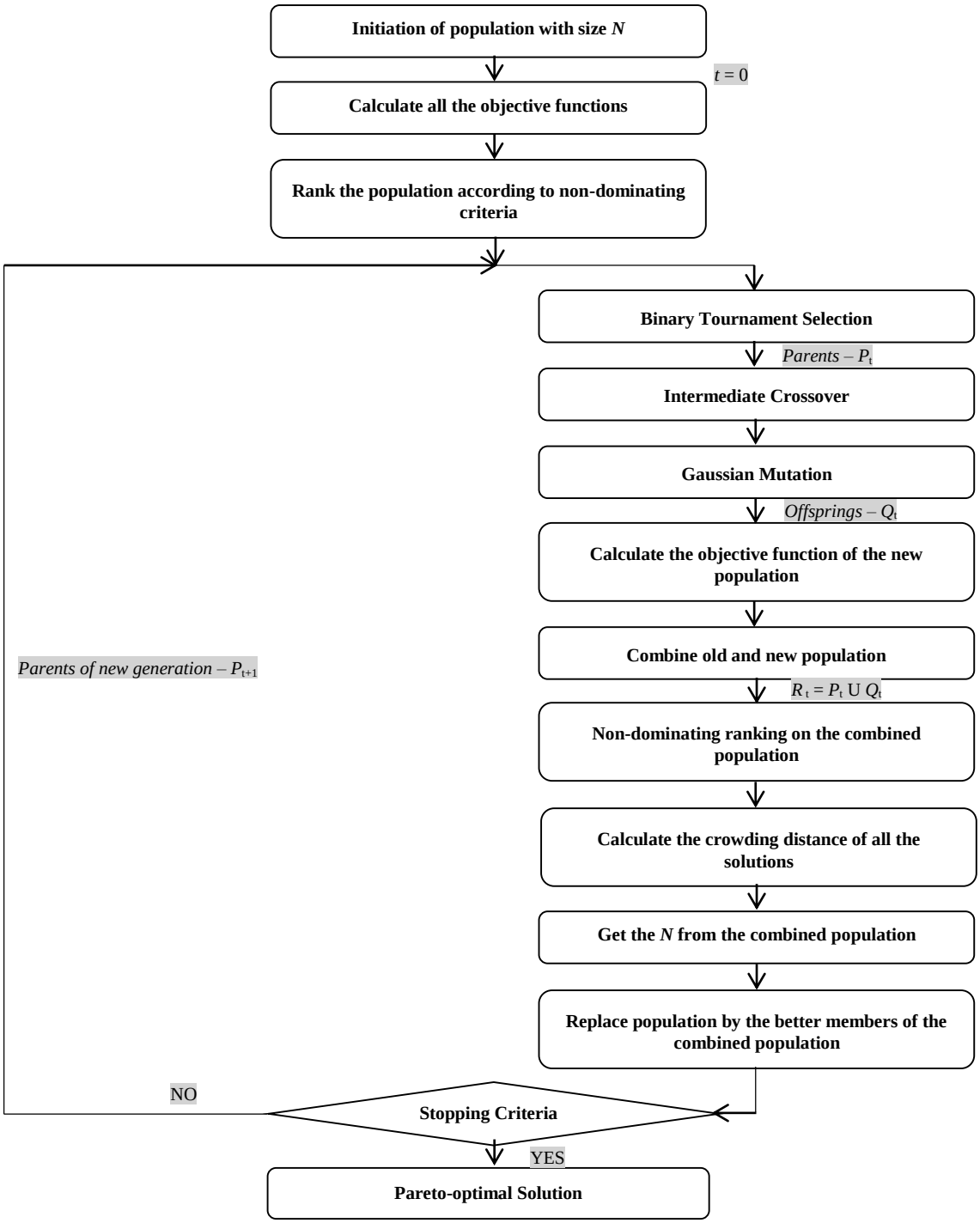

FIGURE 3 Basic structure of NSGA-II algorithm.

2.4. Scenarios

In this research, the baseline scenario was the validated simulation model with the observed pedestrian (160 p/h) and traffic demands (100% of demand factor). A preliminary analysis performed in the simulation demonstrated that pedestrian demands of 330 p/h and 135% of the traffic demand initiated traffic congestion in the coded network. Thus, the effects of both the uniform pedestrian flows and traffic growth (only motor vehicles) were explored at two levels:

- Pedestrian demands: S1) 240 p/h, and S2) 320 p/h;

- Traffic growth: S3) 115%, and S4) 130% demand factors.

For each level, two main demand scenarios were defined: the first level evaluates how vehicle's delay, emissions, and pedestrian's safety change with the increasing of pedestrian traffic demand, assuming no changes on the traffic flows (S1 and S2); the second level analyzes the performance of different pedestrian locations under different traffic flows, assuming no changes on the pedestrians flows (S3 and S4). For all crosswalks locations, the authors modeled the centroids where pedestrians enter and leave in the coded network in the same place as the baseline scenario. Also, pedestrians only walked to the crosswalk independently of its location.

Only crossing conflicts at the selected pedestrian crosswalk were taken into account. It should be mentioned that SSAM identifies not only vehicle-to-pedestrian conflicts, but also pedestrian-to-pedestrian conflicts. In fact, all traffic (vehicles and pedestrians) appear in the *.trj file that is used by SSAM. To address this problem, the authors filtered out any conflict where the maximum speed was lower than 2.2 m/s (which is beyond the natural pedestrian walking speed). The delay and CO_2 emissions per unit distance were given from the vehicle record evaluation. Considering the safety analysis, the conflicts' classification was made according to the FHWA criteria (*27*).

These five scenarios (baseline, S1-4) were then applied, assuming several possible locations for the pedestrian crosswalk (PC) from 5 to 60 meters in increments of 5 meters (relatively to the RBT2 exit section). For all these scenarios, PC was measured from the circulatory ring delimitation of RBT2 to the limit of crosswalk, as illustrated in Figure 2. Three objective functions were optimized for each scenario: delay, CO_2 emissions, and DeltaS.

These functions were used as decision variables of the PC location subject to: 5 meters $\leq$ PC $\leq$ 60 meters. The regression functions were PC vs delay, PC vs CO_2 emissions, and PC vs. DeltaS. A set of 10 optimal solutions was considered for this analysis.

3. RESULTS AND DISCUSSION

3.1. Calibration and Validation

Figure 4 *a* and *b* exhibit the observed and estimated traffic volumes and vehicle speeds before (with VISSIM default parameters) and after the calibration of the traffic model. The results yielded larger improvements for vehicle speed counts while traffic volumes were slightly modified. After the calibration, speeds improved for 75% (n=29) of the links. The remaining speeds were close to the initial speed values. The analysis of the calibration procedure also demonstrated that speed values were more sensitive than links' values to changes in the model parameters.

Table 2 summarizes the traffic calibration results obtained for NRMS, the GEH statistic, as well as the total link volumes before (default) and after the calibration of the model. Both lane-change parameters and simulation resolution were unaffected by the calibration. The results confirmed that the calibrated model parameters improved the GEH statistic. Every link achieved a GEH statistic less than 5, thereby satisfying the calibration criteria. The NRSM went from 0.97 to 0.34. The total difference between observed and estimated link volumes was approximately 1% for all links in the coded network.

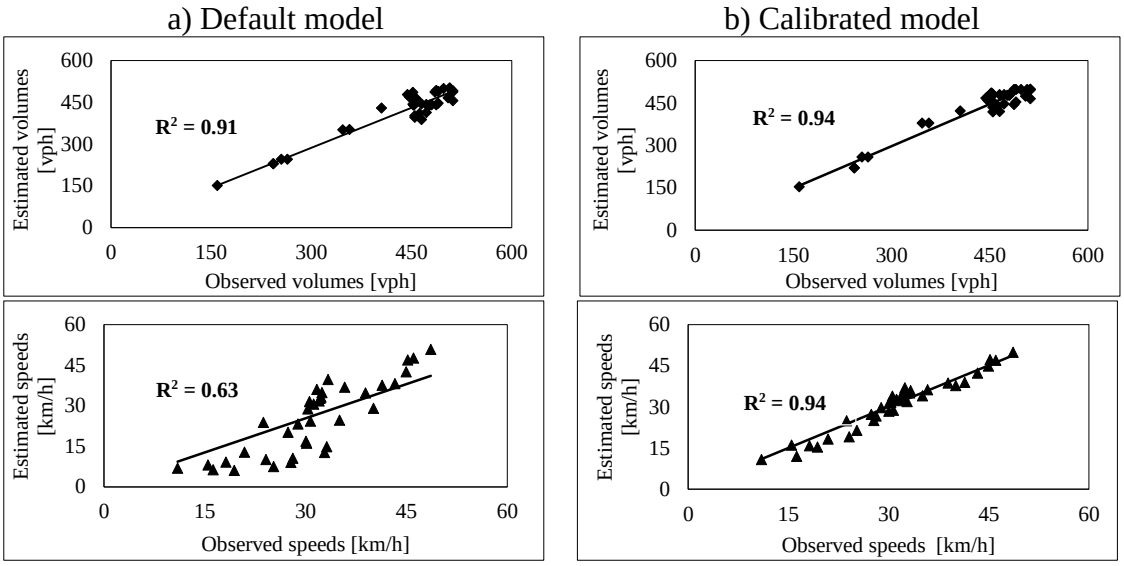

FIGURE 4 Observed vs. Estimated traffic volumes and vehicle's speed: a) default model; b) calibrated model.

TABLE 2 Summary of calibration for the traffic model

	Parameter	Value	NRMS	GEH	Total Link Volumes [vph]
Model Default	Average standstill distance (m)	2.5	0.970	< 5 for 86 % of the cases	15,443
	Additive part of safety distance	2.0			
	Multiple part of safety distance	3.0			
	Minimal gap time (s)	3.0			
	Minimal headway (m)	5.0			
Calibrated Model	Average standstill distance (m)	0.9	0.336	< 5 for 100 % of the cases	15,957
	Additive part of safety distance	1.3			
	Multiple part of safety distance	2.2			
	Minimal gap time (s)	2.8			
	Minimal headway (m)	4.9			

Note: The observed total link volumes was 16,112 vph;
The weight factor (*W*) was set to 0.5.

Concerning validation, a comparison of observed and estimated O/D traffic flows at the roundabouts was conducted using 15 random seed runs (*26*). It showed that 88% of the 34 loop detectors (all feasible movements for RBT1 and RBT2) reached GEH values below 5. These validation results suggested a very good degree of consistency for all cases (*25*). The analysis of the travel times (using 200 floating car runs) pointed out small differences between observed and estimated data (1-3% for all movements). In the case of VSP cumulative probability distributions, the two-sample K-S test at a 5% significance level (*D-value*) for East-West and West-East movements were 0.036 (*p-value* = 0.155) and 0.030 (*p-value* = 0.364), respectively. Similar results were achieved in the remaining movements. Therefore, there was evidence to suggest that the two VSP modes distributions were the same for the observed and estimated routes.

3.2. Regression models

Figure 5 depicts the results for each of the scenarios by varying the location of the pedestrian crosswalk from 5 and 60 meters to the RBT2 exit section. Various models were

tested to identify whether the predictive regression models were a good fit for the analyzed data.

The results indicated that, regardless of the pedestrian demand (baseline, S1 and S2), both delays and CO_2 emissions per unit distance were meaningful for pedestrian crosswalks placed less than 10 meters of the RBT2 exit section (Figure 5 *a-b*, *d-e*). On average, delays and CO_2 emissions at those locations were higher by 25% and 10%, respectively over the average values recorded in the furthest crosswalks (PC>20 meters). Similarly, the difference between vehicle and pedestrian speeds (DeltaS) was found to be small for the crosswalks near the circulatory ring (PC<15 meters), increasing gradually for the crosswalks close to the mid-block segment (PC>30 meters). From that location, it did not vary significantly (~30 km/h). This result is possibly due to lower speeds that vehicles experienced, since they did not reach the cruise speed over the mid-block section between RBT1 and RBT2.

When the levels of traffic demand increased (S3 and S4), the impacts associated with the location of the pedestrian crosswalk assumed a greater influence for locations next to the limit of the RBT2 circulatory carriageway (Figure 5 *j-m*). In real time, the visualization of the simulation demonstrated that the locations that provides stocking capacities of one (PC=5 meters) and two vehicles (PC=10 meters) tend to generate queue in the exit zone, whose extension reaches the circulation ring of RBT2. Subsequently, the traffic from RBT2 almost backed up to RBT1. The values of delay and CO_2 emissions per unit distance on those locations confirmed these findings. Nonetheless, vehicles were stopping at crosswalks close to the RBT2 exit section driving at low speeds, which contributed to improving safety for pedestrians.

These results led to the conclusion that crosswalks close to a roundabout exit section have a negative influence both on the entry capacity and CO_2 emissions, and induce congestion on the second roundabout, especially under high traffic demands. Clearly, the trade-off among performance, environment, and safety was observed as the pedestrian crosswalk is moved along the mid-block section. Rather than the resulting outputs being read from the graphs, the regression equations were employed in the NSGA-II algorithm to identify possible optimal solutions.

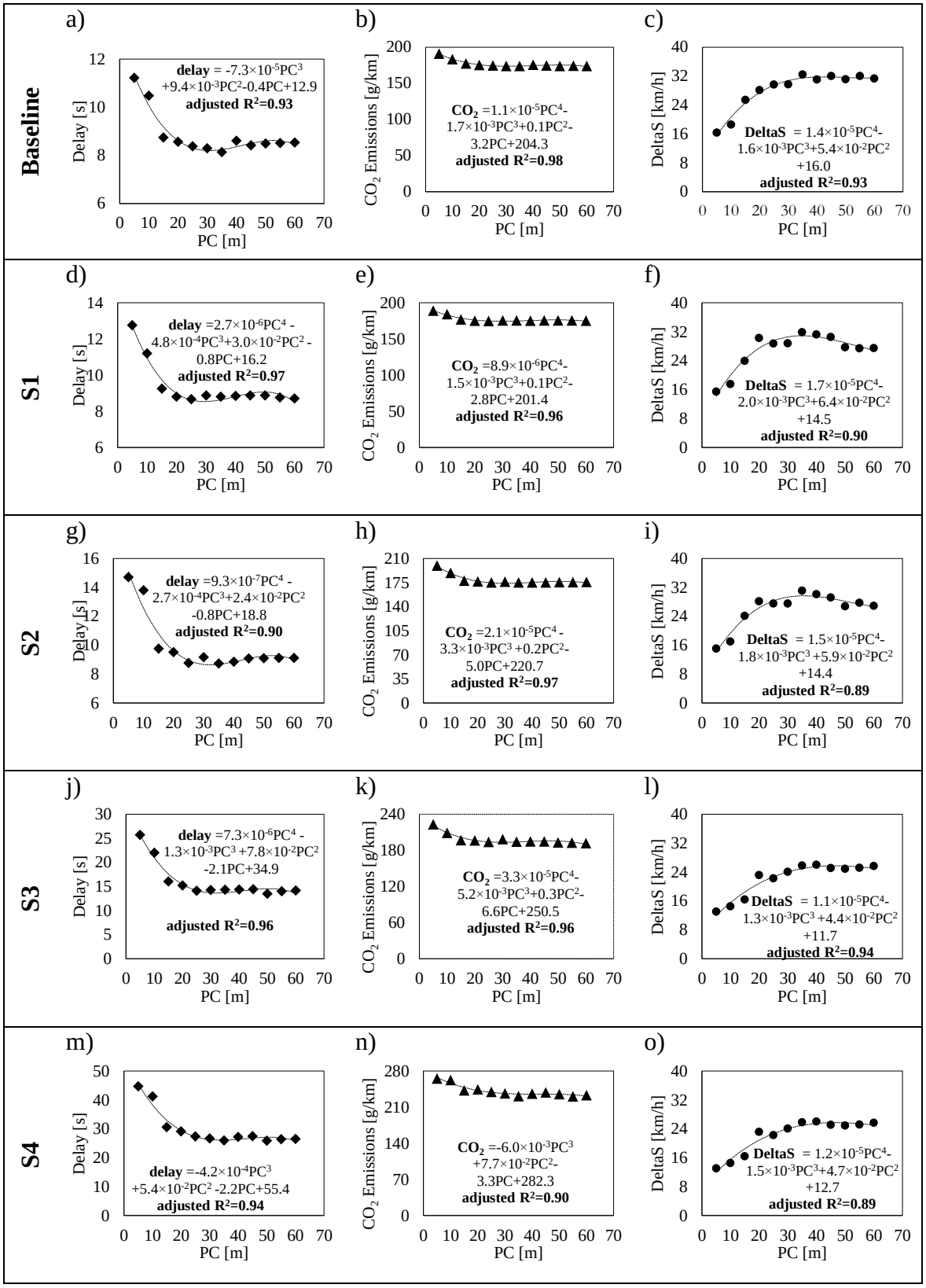

FIGURE 5 Regression models results for scenario PC vs. Delay, PC vs. CO_2 and PC vs. DeltaS: baseline scenario (a, b, c), S1 (d, e, f), S2 (g, h, i), S3 (j, k, l) and S4 (m, n, o).

3.3. Multi-objective optimization

This section presents the main results of the multi-objective optimization of delay, CO_2 emissions and DeltaS as a result of the crosswalk (PC) location along the mid-block section, for each one of the scenarios previously defined (baseline, S1-S4).The analysis of the convergence to POF and the diversity of solutions indicated that a maximum of 300 iterations were sufficient to reach convergence. With reference to crossover and mutation, each solution of the final POF did not vary much with different values of different rates. Thus, the crossover rate was set at 90% and the mutation rate was set at 10%.

Solutions resulting from the evaluated scenarios are summarized in Table 3. Figure 6 illustrates the Pareto fronts estimated from the initial (1st iteration) and final (300th iteration) populations. For each scenario, a 3-D scatter plot with the three objective functions – CO_2 Emissions (x-axis), delay (y-axis), DeltaS (z-axis) – as a function of PC is shown.

It was confirmed that the approximate Pareto front moves markedly in the lower-left direction (Figure 6-*a*) in the baseline scenario, which means that crosswalks placed more than 32 meters to the circulatory ring are not good solutions considering the current traffic conditions. It was clear that adopting a crosswalk placed at 15 meters away from the RBT2 section (Solution 6), average delay and CO_2 emissions per unit distance decreased by 19% and 7% respectively, while the difference between vehicles and safety speed was increased by no less than 37% in comparison with the lower-level solution (Solution 1). Crosswalks located at 20 and 31 meters away from RBT2 are also proved as optimal solutions on the selected case study (Table 3). Similar results were found in S1 and S2 scenarios.

Regarding the high traffic demand scenarios (S3 and S4), the final Pareto front moved in the upper-left and lower-right directions, that is, the solutions associated to the faraway (PC = 60 meters) and nearest crosswalks (PC = 5 meters) respectively from the RBT2 section. In the first case, this was explained by the lower values of DeltaS (~24 km/h) on those locations in comparison to the lower demand scenarios, i.e., baseline, S1 and S2 (~30 km/h). Also, the average values of Delay and CO_2 emissions decreased as the crosswalk was placed farther away from the RBT2 exit section (Figure 5 *j-k*, *n-m*). For instance, if one adopted a crosswalk 60 meters away from the exit section (assuming the traffic conditions of S4), then one could save up to 43% and 13% in average delay and CO_2 emissions, respectively, while DeltaS increases by 74% (Table 3). In the second case, high congestion levels resulted in low DeltaS values near to RBT2 exit section (~14 km/h), and therefore such location was pointed out as a solution to be implemented at the arterial.

These findings suggested that the location of the crosswalk far away from the circulatory carriageway can also be used (PC=55/60 meters), especially under high traffic conditions. In such cases, safety for pedestrians was perceived as slightly negatively impacted, since the spacing of the roundabouts constrains the vehicles speeds at the mid-block segments. However, locating the crosswalk in further distances from the downstream roundabout (e.g. PC=80 meters) affected the traffic operations in the upstream roundabout. Although the crosswalks near to the exit section were undoubtedly safe for pedestrians, their practical implementation would not provide any global competition in capacity and environmental point of views. Previous research demonstrated that for high pedestrian demand (P>400 p/h) at 70% of the saturation rate, a crosswalk was ineffective on traffic operations when located less than 15 meters away from the roundabout delimitation (*5*).

TABLE 3 Solution lists of the pedestrian crosswalk locations (after 300 iterations)

Scenario	Solution No.	PC [m]	Delay [s]	CO_2 [g/km]	DeltaS [km/h]
Baseline	1	5.000	11.310	191.307	17.147
	2	5.000	11.310	191.307	17.147
	3	7.226	10.710	187.133	18.236
	4	9.033	10.280	184.380	19.289
	5	12.338	9.618	180.653	21.465
	6	15.238	9.160	178.606	23.486
	7	15.993	9.057	178.240	24.012
	8	20.438	8.587	177.297	26.956
	9	31.303	8.188	181.696	31.694
	10	31.303	8.188	181.696	31.694
S1	1	5.000	12.918	190.021	15.856
	2	5.000	12.918	190.021	15.856
	3	5.413	12.701	189.273	16.067
	4	7.358	11.786	186.102	17.210
	5	11.001	10.477	181.544	19.811
	6	14.086	9.715	178.865	22.238
	7	18.541	9.047	176.479	25.670
	8	27.115	8.678	175.072	30.550
	9	27.627	8.679	175.069	30.735
	10	27.627	8.679	175.069	30.735
S2	1	5.000	15.154	200.267	15.643
	2	5.000	15.154	200.267	15.643
	3	8.010	13.459	191.774	17.280
	4	11.347	11.962	184.996	19.522
	5	14.496	10.871	180.647	21.811
	6	18.544	9.862	177.284	24.682
	7	20.875	9.451	176.198	26.181
	8	27.412	8.819	175.213	29.339
	9	32.253	8.710	175.449	30.443
	10	32.253	8.710	175.449	30.443
S3	1	5.000	26.223	223.778	12.674
	2	5.000	26.223	223.778	12.674
	3	5.388	25.684	222.197	12.813
	4	8.920	21.541	210.476	14.371
	5	11.272	19.463	205.001	15.621
	6	15.223	16.962	199.061	17.888
	7	22.958	14.620	195.158	22.069
	8	55.666	13.919	192.001	24.878
	9	56.744	13.925	191.953	25.006
	10	56.744	13.925	191.953	25.006
S4	1	5.000	45.628	267.678	13.721
	2	5.000	45.628	267.678	13.721
	3	8.275	40.557	259.975	14.146
	4	10.311	37.881	255.866	15.208
	5	14.226	33.670	249.299	17.415
	6	17.756	30.823	244.731	19.381
	7	21.918	28.465	240.772	21.420
	8	27.500	26.694	237.448	23.360
	9	60.000	25.899	231.841	23.937
	10	60.000	25.899	231.841	23.937

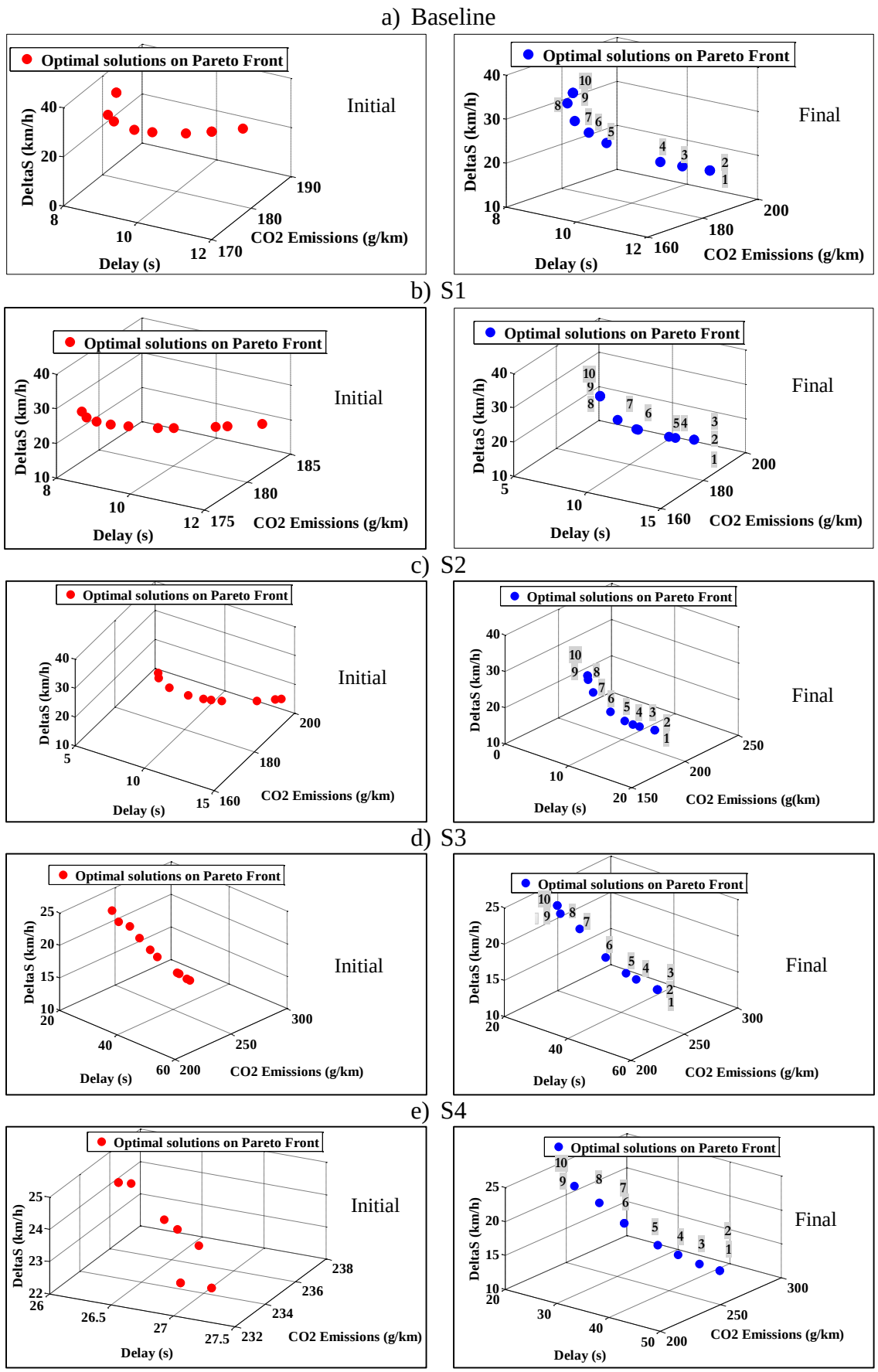

FIGURE 6 The approximate initial (left) and final (right) Pareto front: a) Baseline; b) S1; c) S2; d) S3 and e) S4.

4. CONCLUSIONS

This paper explored different pedestrian crosswalk locations between two closely spaced roundabouts in terms of capacity/delays, the environment, and pedestrian's safety. The analysis was based on a microsimulation approach, using a traffic model combined with emission and safety models. Three regression models were established to express the trade-off among delay, CO_2 emissions per unit distance, and the difference between vehicles' and pedestrians' speeds as a function of several pedestrian crosswalk locations along the mid-block sub-segment. As a solution algorithm for the models, NSGA-II was used to search the optimal solutions for the proposed problem.

Crosswalks near the circulating carriageway (< 10 meters) were associated with weak performance levels and high CO_2 emissions rates. The distances of 15, 20 and 30 meters were predicted to be appropriate in this an interrupted traffic facility, regardless of the pedestrian and traffic demands. It was also found that for high traffic flows the location of the crosswalks near the mid-block (55/60 meters) improved the capacity and emissions use without affecting significantly the safety of pedestrians.

This methodology can be tailored to analyze other arterials with closely-spaced roundabouts in which crosswalks are located at the mid-block segments, and whose impacts on traffic are not thoroughly evaluated. Obviously, vehicular capacity or emissions used are not the only considerations for the assessment of crosswalks locations at roundabouts. The improvement of the safety for pedestrians remains the most important "selling point" of any good crosswalk location. Still, the findings in this study provide relevant information for local authorities for the balanced implementation of a pedestrian crosswalk by taking into account the trade-off among capacity, environment, and safety. A site's specific operational conditions may favor other pedestrian crosswalks locations and, as a result, the models should be calibrated for each location (with its own traffic, pedestrian demands, and driving patterns).

There were three main limitations that must be outlined. The first was that only the impacts on the pedestrian crosswalk were taken into account; the remaining crosswalks and the pedestrian patterns were excluded from this analysis. The second was the absence of specific measures that can reflect the pedestrian performance, as delay. The third limitation was that pedestrians only walked to the crosswalk.

Therefore, future work is needed to enhance and calibrate the pedestrians patterns along the coding network as well as to include those additional measures that can reflect the impact on pedestrians by moving a crosswalk along the arterial. A relationship between the crosswalk location and speed could also be examined. The assessment of additional objective environmental variables (such as carbon monoxide, hydrocarbons or nitrogen oxides) to the optimization procedure would be explored in future work.

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