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MODELAÇÃO INTERPRETATIVA DA SEGURANÇA E EMISSÕES EM CORREDORES DE ROTUNDAS E SEMÁFOROS

INTERPRETED MODELLING FOR SAFETY AND EMISSIONS AT ROUNDABOUTS AND TRAFFIC SIGNALS IN CORRIDORS

Tese apresentada à Universidade de Aveiro para cumprimento dos requisitos necessários à obtenção do grau de Doutor em Engenharia Mecânica, realizada sob a orientação científica da Professora Doutora Margarida Coelho, Professora Auxiliar do Departamento de Engenharia Mecânica da Universidade de Aveiro, e do Professor Doutor Nagui Rouphail, Diretor do Institute for Transportation and Education (ITRE) da Universidade do Estado da Carolina do Norte, Raleigh.

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palavras-chave Corredores, Rotundas, Semáforos, Emissões, Segurança, Modelação, Análise Multiobjectivo

resumo

Estudos anteriores demonstram que os desempenhos operacional, ambiental e ao nível da segurança para os peões de uma rotunda dependem das suas características geométricas e dos fluxos de tráfego e de peões. Porém, a implementação de uma rotunda pode traduzir-se numa avaliação de compromisso entre as variáveis da capacidade, emissões de poluentes e segurança. Para além disso, a informação relativa às potencialidades de rotundas interdependentes ao longo de corredores é diminuta.

Assim, esta tese de doutoramento centra-se na compreensão dos impactos no desempenho do tráfego, emissões e segurança dos peões inerentes ao funcionamento de corredores de rotundas. Uma das contribuições deste trabalho é o desenvolvimento de uma metodologia capaz de avaliar as características geométricas e operacionais dos corredores de forma integrada. Os principais objetivos desta tese são: 1) analisar o impacto dos elementos geométricos dos corredores de rotundas em termos dos perfis de aceleração e das emissões; 2) investigar as principais diferenças na distribuição espacial das emissões entre rotundas isoladas e em corredores; 3) comparar os desempenhos operacional e ambiental de corredores com diferentes tipos de interseções tais como rotundas convencionais, turbo-rotundas, cruzamentos semaforizados e interseções prioritárias; e 4) dimensionar um corredor de modo a otimizar o atraso dos veículos, e emissões de poluentes globais (dióxido de carbono – CO_2) e locais (monóxido de carbono – CO, óxidos de azoto – NO_x e hidrocarbonetos – HC).

O trabalho de monitorização experimental consistiu na recolha de dados da dinâmica do veículo, e volumes de tráfego e pedonais. Para tal, foram selecionados 12 corredores com rotundas convencionais em Portugal, Espanha e Estados Unidos da América, 3 corredores com turbo-rotundas na Holanda e ainda um corredor misto com rotundas, sinais luminosos e interseções prioritárias em Portugal. No total foram recolhidos aproximadamente 2000 km de dados da dinâmica do veículo, num total de 50 h. Foi utilizada uma plataforma de modelação microscópica de tráfego (VISSIM), emissões (Vehicle Specific Power – VSP) e segurança (Surrogate Safety Assessment Model – SSAM) de modo a replicar as condições de tráfego locais e avaliar cenários alternativos.

Os resultados mostraram que o espaçamento entre interseções teve um impacto significativo nos perfis de aceleração e emissões. No entanto, tal não se verificou para o ângulo de deflexão de entrada (elemento fulcral nos níveis de emissões em rotundas isoladas), nomeadamente nos casos em que as rotundas adjacentes estavam próximas (< 200 m). A implementação de corredores de turbo-rotundas conduziu ao aumento das emissões face a um corredor convencional de rotundas com duas vias (1-5%, dependendo do poluente). A relocalização de uma rotunda ou turbo-rotunda no interior do corredor, de modo a aumentar o espaçamento em relação a uma interseção a jusante e/ou a montante, levou a uma melhoria das emissões do corredor. Conclui-se também que em condições de elevado tráfego de atravessamento e não uniformemente distribuído entre as vias principais e secundárias, os veículos ao longo de um corredor com rotundas produziram menos emissões (~5%) face a um corredor com semáforos, mas emitiram mais gases (~12%) comparativamente a um corredor de interseções prioritárias.

Esta investigação contribuiu para o estado de arte através da análise detalhada dos benefícios e limitações dos corredores de rotundas tanto ao nível geométrico como ao nível operacional. Adicionalmente, estabeleceram-se várias correlações entre variáveis geométricas do corredor (espaçamento), localização das passadeiras e volume de tráfego, o atraso, e emissões de CO_2, CO, NO_X e HC. Demonstrou-se ainda que a implementação de uma interseção ao longo do corredor com a finalidade de minimizar o CO_2 pode não resultar na melhoria de outras variáveis tais como o CO ou NO_X. Esta metodologia serve como apoio à decisão e, portanto, permite avaliar o tipo de interseção mais adequado de acordo com as especificidades de cada local.

keywords Corridors, Roundabouts, Traffic Lights, Emissions, Safety, Modeling, Multi-objective analysis

abstract Scientific research has demonstrated that the operational, environmental and safety performance for pedestrians depend on the geometric and traffic stream characteristics of the roundabout. However, the implementation of roundabouts may result in a trade-off among capacity, environmental, and safety variables. Also, little is known about the potential impacts for traffic from the use of functionally interdependent roundabouts in series along corridors. Thus, this doctoral thesis stresses the importance of understanding in how roundabout corridors affect traffic performance, vehicular emissions and safety for vulnerable users as pedestrians. The development of a methodology capable of integrating corridor's geometric and operational elements is a contribution of this work. The main objectives of the thesis are as follows: 1) to analyze the effect of corridor's design features in the acceleration patterns and emissions; 2) to understand the differences in the spatial distribution of emissions between roundabouts in isolation and along corridors; 3) to compare corridors with different forms of intersections such as conventional roundabouts, turbo-roundabouts, traffic lights and stop-controlled intersections; and 4) to design corridor-specific characteristics to optimize vehicle delay, and global (carbon dioxide – CO_2) and local (carbon monoxide – CO, nitrogen oxides – NO_X and hydrocarbons – HC) pollutant emissions.

Vehicle dynamics along with traffic and pedestrian flow data were collected from 12 corridors with conventional roundabouts located in Portugal, Spain and in the United States, 3 turbo-roundabout corridors in the Netherlands, and 1 mixed roundabout/traffic-lights/stop-controlled corridor in Portugal. Data for approximately 2,000 km of road coverage over the course of 50 h have been collected. Subsequently, a microscopic platform of traffic (VISSIM), emissions (Vehicle Specific Power – VSP) and safety (Surrogate Safety Assessment Model – SSAM) was introduced to faithful reproduce site-specific operations and to examine different alternative scenarios.

The main research findings showed that the spacing between intersections influenced vehicles acceleration-deceleration patterns and emissions. In contrast, the deflection angle at the entrances (element that impacts emissions on isolated roundabouts) impacted slightly on the spatial distribution of emissions. It was also found that the optimal crosswalk locations along mid-block sections in roundabout corridor was generally controlled by spacing, especially in the case of short spacing between intersections (< 200 m). The implementation of turbo-roundabout in series along corridors increased emissions compared to conventional two-lane roundabout corridors (1-5%, depending on the pollutant). By changing the location of a roundabout or turbo-roundabout to increase spacing in relation to upstream/downstream intersection resulted in an improvement of corridor emissions. Under conditions of high through traffic and unbalanced traffic flows between main roads and minor roads, vehicles along roundabout corridors produced fewer emissions (~5%) than did vehicles along signalized corridors, but they emitted more gases (~12%) compared to a corridor with stop-controlled intersections. This research contributed to the current state-of-art by proving a full comprehension about the operational and geometric benefits and limitations of roundabout corridors. It also established correlations between geometric variable of corridors (spacing), crosswalk locations or traffic streams, and delay, and CO_2, CO, NO_X or HC variables. With this research, it has been demonstrated that the implementation of a given intersection form within a corridor focused on minimizing CO_2 may not be translated to other variables such as CO or NO_X. Therefore, the develop methodology is a decision supporting tool capable of assessing and selecting suitable traffic controls according the site-specific needs.

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NOMENCLATURES

a	Vehicle instantaneous acceleration or deceleration [$m.s^{-2}$]
AADT	Average Annual Daily Traffic
aaSIDRA	aaTraffic Signalized & unsignalized Intersection Design and Research Aid
AIMSUN	Advanced Interactive Microscopic Simulator for Urban and Non-Urban Networks
AIRE	Analysis of Instantaneous Road Emissions
AWSC	All Way Stop Control
B	Model Predictor Coefficient
CAL3QHC	Environmental Protection Agency Recommended Intersection Dispersion Model
CI	Confidence Interval
C_n	Choice set that the decision maker *n* faces
CNEM	Comprehensive Modal Emissions Model
CO	Carbon Monoxide
COPERT	Computer Programme for calculating emissions for Road Traffic
CO_2	Carbon Dioxide
CV	Coefficient of Variability
DeltaS	Relative difference between vehicles and pedestrians speed [$m.s^{-1}$] or [$km.h^{-1}$]
DPV	Diesel Passenger Vehicles
DTA	Dynamic Traffic Assignment
d_i^v	Control delay by vehicle [$s.veh^{-1}$]
d/c	demand-to-capacity ratio
EC	European Commission
E_i	Emissions of a specific pollutant per vehicle for each average speed profile [$g.veh^{-1}$]
E_{ij}	Total emissions for source pollutant [g]
E_{jK}	Total emissions for sub-segment *K* and source pollutant *j* [g]
EMEP/EEA	European Monitoring and Evaluation Programme by European Environmental Agency
E_{TR}	Hourly emissions at the turbo-roundabout [g]
EU28	European Union 28 Countries
E_I	Emissions of a specific pollutant per vehicle for vehicles that do not stop at the roundabout or turbo-roundabout [$g.veh^{-1}$]

$\mathbf{E_{II}}$	Emissions of a specific pollutant per vehicle for vehicles that stop once at the roundabout or turbo-roundabout [$g.veh^{-1}$]
$\mathbf{E_{III}}$	Emissions of a specific pollutant per vehicle for vehicles that stop more than once at the roundabout or turbo-roundabout [$g.veh^{-1}$]
FCT	Portuguese Science and Technology Foundation
FEDER	European Community Fund
FHWA	Federal Highway Administration
F_i	Non-dominated fronts
F_{ijK}	Emission factor for pollutant *j* in second of travel *I* on sub segment *K* [$g.s^{-1}$]
FLAD	Luso-American Foundation
F_{mj}	Emission factor for pollutant *j* in label for second of travel *m* [$g.s^{-1}$]
GA	Genetic Algorithm
GEH	Geoffrey E. Havers Statistic
gen	Number of generations
GPS	Global Positioning System
GPV	Gasoline Passenger Vehicles
grade	Terrain gradient [%]
HC	Hydrocarbons
HCM	Highway Capacity Manual
HDV	Heavy-Duty Vehicles
HEV	Hybrid Electric Vehicles
I	Last Analyzed Link
K-S	Two-sample Kolmogorov-Smirnov test
LCDV	Light Commercial Diesel Vehicles
LDV	Light Duty Vehicles
LDDT	Light Duty Diesel Trucks
LDDV	Light Duty Diesel Vehicles
LOS	Level of Service
LPDV	Light Passenger Diesel Vehicles
LPGV	Light Passenger Gasoline Vehicles
LPV	Light Passenger Vehicles
MAPE	Mean Absolute Percent Error
ML	Multi-lane Roundabout
MNL	Multinomial Logit Model
MOVES	MOtor Vehicle Emission Simulator

mph	Miles per hour
$\boldsymbol{N}$	Set of total links in VISSIM modeling
NCHRP	National Cooperative Highway Research Program
NCSU	North Carolina State University
$\boldsymbol{N_K}$	Travel time on sub-segment *K* [s]
$\boldsymbol{N_m}$	Number of seconds
$\mathbf{NO_X}$	Nitrogen Oxides
NRMS	Normalized Root Mean Square
$\boldsymbol{N_S}$	Population size
NSGA-II	Fast Nondominated Sorting Genetic Algorithm
OBD	On-Board Diagnostic System
O-D	Origin-Destination matrices
PC	Pedestrian Crosswalk Location [m]
pcu	Passenger Car Unit
PEMS	Portable Emissions Measurement System
PM	Particulate Matter
$\mathbf{PM_{2.5}}$	Particulate Matter of less than 2.5μm
$\mathbf{PM_{10}}$	Particulate Matter of less than 10μm
POF	Pareto Approximate Front
$\mathbf{P_I}$	Proportion of vehicles that do not stop at the roundabout
$\mathbf{P_{II}}$	Proportion of vehicles that stop once at the roundabout
$\mathbf{P_{III}}$	Proportion of vehicles that stop more than once at the roundabout
$\boldsymbol{Q_{conf}}$	Conflicting flow in roundabout or turbo-roundabout [vph]
$\boldsymbol{Q_{in}}$	Entry traffic flow in roundabout or turbo-roundabout [vph]
$\boldsymbol{Q_{total}}$	Sum of the entry and conflicting traffic flows [vph]
RIA	Roundabout Influence Area
RMSPE	Root Mean Square Percentage Error
$\boldsymbol{S}$	Spacing between intersections [m]
$\boldsymbol{SE}$	Standard error around coefficient *B* of the model predictor
$\boldsymbol{s_i}$	Observed speeds for link *i* [$m.s^{-1}$]
$\boldsymbol{S_{max}}$	Maximum spacing length that allows a stocking capacity of one vehicle [m]
SPSA	Simultaneous Perturbation Stochastic Approximation
SSAM	Surrogate Safety Assessment Model
S-PARAMICS	PARAllel MICroscopic traffic Simulator
$\tilde{s}\ (\theta)_I$	Estimated speeds for link *i* [$m.s^{-1}$]

t	Number of generations
T	Total number of time periods
T_D	Total distance travelled by vehicle [km]
TEDS	Traffic & Emission Decision Support
TR	Turbo-Roundabout
TREM	Transport Emission Model for Line Sources
TTC	Time-to-collision [s]
TWSC	Two-way stop control
T1 PC	Tier 1 Passenger Car
T2 PC	Tier 2 Passenger Car
$U_{i,n}$	Utility function
UK	United Kingdom
US	United States
v	Vehicle instantaneous speed [$m.s^{-1}$]
v_i	Observed link volumes for link i [vph]
$V_{i,n}$	Systematic part of utility which is a linear function to predict the probability that decision maker n chooses alternative i
VISSIM	Verkehr In Städten SIMulationsmodell
vpd	vehicles per day
vph	vehicles per hour
vph/lane	vehicles per hour per lane
VSP	Vehicle Specific Power [$kW.ton^{-1}$]
VT-Micro	Virginia Tech microscopic energy and emission model
$\tilde{v}(\theta)_i$	Estimated link volumes for link i [vph]
v/c	Volume-to-capacity ratio
W	Weight to assign more or less value to volumes or speeds
Wald	Chi-square test
$\beta_{2,0}$	Intercept for outcome P_{II}
$\beta_{2,1}$	Coefficient for outcome P_{II}
$\beta_{3,0}$	Intercept for outcome P_{III}
$\beta_{3,1}$	Coefficient for outcome P_{III}
$\varepsilon_{i,n}$	Error between the systematic part of utility and the true utility assigned by user n to alternative i

1. INTRODUCTION

The introduction chapter offers a general statement of the thesis. It proceeds in five parts. **Section 1.1** sets the motivation for the research. The main research objectives and contributions are described in **Sections 1.2** and **1.3**, respectively. The background information is given in **Section 1.4** followed by the structure of the thesis in **Section 1.5**.

1.1. Research Motivation

1.1.1. Corridors with Roundabouts

Roundabouts are increasingly recognized as an intersection control strategy that can meet multiple performance goals concerning the traffic operation and safety, as well as fulfill societal goals related to livability, sustainability or economic development (1). This trend has led that some local authorities in the United States (US) and Europe approved the use of a series of roundabouts on an arterial rather than the conventional solution of coordinating signalized intersections. Some of the main advantages roundabout corridors are: *1*) possibility of U-turns on access restricted roadways that prevent some of the crashes related to the median openings (2); *2*) flexibility in maximizing intersection capacity without the need for excess turn lane storage or additional receiving lanes (1); *3*) higher likelihood to having better travel time, especially in the case of unevenly-spaced intersections (1).

As defined in this doctoral thesis, a roundabout corridor includes a series of three or more roundabouts that function interdependently on an arterial (3), as shown in **Figure 1.1**. However, corridors with only two closely-spaced roundabouts are also considered.

a) Six Roundabouts – Braga, Portugal   b) Six Roundabouts – Malaga, Spain

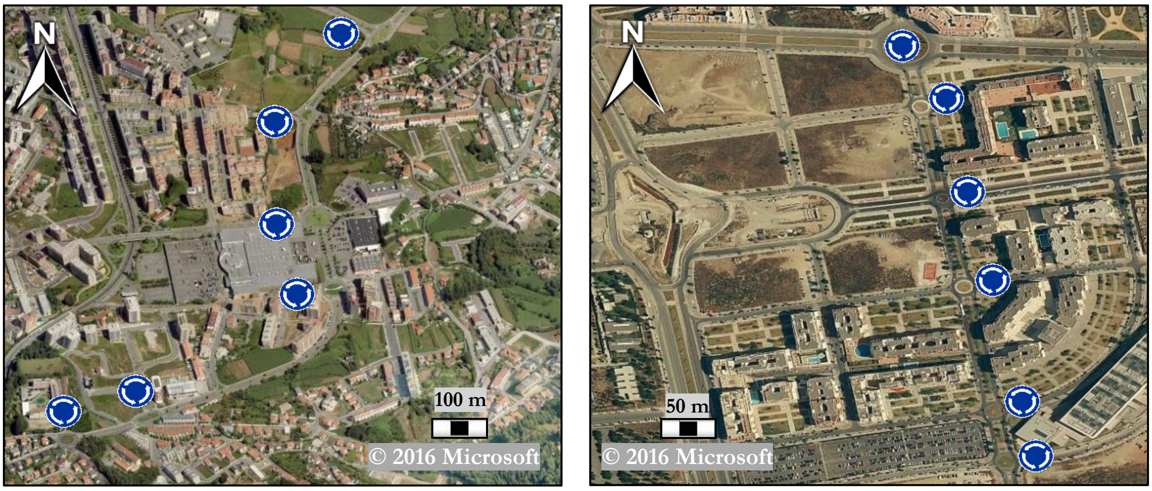

Figure 1.1 Roundabout Corridor [adapted from Bing Maps].

While some studies suggest that interdependent roundabouts on a corridor are successful in fulfilling performance goals, little is known about the efficiency of this alternative as compared to a series of coordinated signalized intersections (3). Roundabouts in series on an arterial have unique operational characteristics compared to their intersection counterparts. Fundamentally, roundabouts do not allow the moving platoons of vehicles to maximize traffic performance owing to the gap acceptance principles. Vehicles also experience a delay based on the geometry of each roundabout due to the low approach speeds, and therefore they may produce more emissions (3, 4).

Roundabouts in close proximity to each other (**Figure 1.2**) can exist along roundabout corridors. In such cases, the expected queue length at each roundabout may be relevant. Closely-spaced roundabouts may improve safety by calming the traffic on the major roads because drivers may be reluctant to accelerate to the cruise speed at the mid-block section if they are also required to slow again towards the next roundabout (5). However, traffic congestion and emissions levels along a corridor with closely-spaced roundabouts may increase in the conditions of intense traffic, and in areas where some pedestrian activity is expected. National Cooperative Highway Research Program (NCHRP) Report 672 provides some considerations about the design of closely-spaced roundabouts, but only focused on the estimation of 95th-percentile queues to check the extent of the queued space (5).

Figure 1.2 Closely-spaced roundabouts in Ourense, Spain [adapted from Google Earth].

Existing research in roundabout corridors has focused on their traffic performance. Travel time is a natural performance measure for roundabout and signalized corridors (2). Roundabouts have higher geometric delay compared to signalized intersections by virtue of their shape; therefore, defining travel time measures is of paramount interest.

To provide a wide range of measurement and evaluation methods for comparing the performance of roundabout corridors, Rodegerdts et al. conducted a study in 58 US corridors (2). Also, field measured vehicle travel time among corridors with roundabouts, signalized and two-way stop controlled intersections was compared. The findings suggested that roundabout corridors have a good likelihood of improving travel time, but site-specific operational conditions may benefit signalized corridors. Another conclusion was that a corridor with evenly-spaced roundabouts exhibited a higher propensity for having lower travel time compared to a signalized configuration (2).

A study of a corridor with four roundabouts (800 m in length and a traffic flow over 20,000 vehicles per day – vpd) concluded that after installing roundabouts, both travel time and frequency of crashes decreased compared to a prior signalized corridor solution (6). Other authors found improvements in the Level of Services (LOS) after the installation of roundabout corridors in the US (7, 8). Krogscheepers and Watters explained that, compared with a fixed-cycle signalized corridor, six roundabouts in series along a rural corridor offered operational advantages over traffic lights, but less capacity levels during some peak periods (9).

Very few studies have addressed the influence of corridors on fuel consumption or emissions or in how design features of corridors impact traffic operations. AaSIDRA (acronym for aaTraffic Signalized & unsignalized Intersection Design and Research Aid) model includes a lane-based micro-analytical network model that offers relevant performance and emission data for roundabout corridors based on corridor's geometric and operational characteristics. Nevertheless, the model lacks for an appropriate evaluation in real-world roundabout corridors and comparison with other analytical and simulation tools (10).

1.1.2. Signalized Corridors

Signalized corridors analysis is a mature area of research, and some of their operational fundamentals can be associated to those of roundabouts corridors for variables such as travel time and vehicle delay (2). The Highway Capacity Manual (HCM) 2010 includes a methodology for assessing the quality of service on an urban street using measures for four travel models (cars, transit buses, pedestrians and bicycles) based on user perceptions. Traveler perception model in the HCM is given as performance measure to enable multimodal evaluation (but is not used to determine LOS) (11). Two reports from NCHRP Project 03-79 (12, 13) also contributed to methodologies and services measures considered in HCM 2010 by including real-time performance measurements for urban streets (12). Bonneson et al. (13) developed different procedures for predicting running time, delay and stop rate and included in the HCM 2010 urban street procedure (14). Although these procedures can be applicable to roundabout corridors, some of them were not properly calibrated and validated (13).

Many empirical studies have shown a positive relationship between emissions and fuel consumption, and delays at traffic signals (15-18). Researchers have been developed adaptive and dynamic traffic signal control algorithms for signalized corridors either for optimizing traffic delay (19, 20) or for lowering fuel consumption and emissions rates (21-26).

One of major issues of estimating emissions for signalized corridors is that the average traffic speed, per se, cannot completely characterize emissions of those traffic facilities (27). For example, a vehicle cruising at 70 km/h for 20 s followed by idling at a traffic light for another 20 s consumed more fuel and generated higher emissions than the same vehicle cruising at 35 km/h for 40 s (28).

The emission comparisons between signalized and roundabout corridors is a topic poorly explored. Bergh et al. analyzed the performance of a corridor with ten signalized and one stop-controlled intersection in the US, and compared with a proposed situation of implementing a roundabout. They pointed out the land use constraints and unbalanced traffic flow between major and minor arterials as motives to preclude the roundabout as a traffic control (29). One corridor with 21 stop-controlled and 11 signalized intersections in Canada was compared to an equivalent corridor where roundabouts replaced all signalized intersections. Despite the reduction in emissions up to 20% in the roundabout influence area, the proposed plane increased emissions at the corridor level in almost 30%. This was mostly due to the spillover effect in the other areas of the network (30).

1.1.3. Mixed Traffic Lights/Roundabouts Corridors

Research also has been conducted on corridors containing traffic lights, roundabouts, and other forms of intersections (31-34). The findings were not clear about the efficiency of roundabouts. Bared and Edara showed that delay did not vary through the signalization alternative when roundabout operated below capacity, but the signalized intersection outperformed roundabout under high traffic flows (31). The research of Hallmark et al. evidenced that, under uncongested conditions and depending on the driving style, traffic and intersection characteristics, roundabouts performed worse than stop-controlled intersection, or signalized intersection on a same corridor (34). Coelho et al. developed TEDS (acronymic for Traffic & Emission Decision Support) tool to evaluate emissions in singularities located in corridors. The case study was an urban highway corridor in Portugal containing a single-lane roundabout, a traffic signal intersection, and a speed control traffic signal. Roundabout generated similar emission amounts than traffic lights, but much more than those obtained from speed control signal in hydrocarbon (HC) and dioxide carbon (CO_2) emissions (32).

1.1.4. Research Gaps

The traffic performance, safety and environmental characteristics of roundabouts has been well explored nowadays, particularly those installed at isolated intersections. Studies of roundabouts and signalized corridors as well as corridors with mixed traffic control treatments also provide insight onto service measures and analysis methodologies. Because of the evidence currently available, it seems fair to recognize that the implementation of roundabout corridors is a growing interest by engineers and traffic planners.

From the points discussed in the previous sections, the following gaps were identified:

- Qualitative and quantitative information on the environmental and energy performance of a set of functionally interdependent roundabouts on arterials is lacking. Vehicle speeds and acceleration-deceleration cycles, queue formation or spatial distribution of the emissions may be sensitive for optimizing specific geometric elements of the corridor such as the spacing between roundabouts and the entry deflection angle;
- Understanding the operational and environmental differences between roundabouts in isolation and along corridors is critical. Some of the design features that impact acceleration and emissions distributions at isolated roundabouts and along roundabout corridors may be different;
- There is no robust comparison between corridors with roundabouts (both traditional layouts and innovative layouts as is the case of turbo-roundabouts) and other forms of intersections along arterials such as traffic lights and stop-controlled intersections under different traffic conditions (e.g. traffic flows or directional split of the entry traffic), speed limits or geometric characteristics (e.g. spacing between intersections or roundabouts size). Also, a corridor-specific analysis methodology capable of selecting the suitable form of intersection is somewhat lacking;
- For a certain problem, a multi-objective optimization is able to optimize local pollutants (which have direct effects on human health) and CO_2 criteria (which is relevant for

global warming), but no studies addressed an issue of minimizing local and global pollutants simultaneously along roundabout corridors;

- Neither previous studies addressed the safety impacts of corridors with roundabouts on pedestrians, nor they included hypothetic trade-offs among capacity, emissions, and pedestrian safety.

1.2. Research Objectives

The goal of this research is to quantify and assess the impact of corridors on traffic performance, global and local pollutant emissions and safety for pedestrians. This PhD thesis is focused on the main specificities of corridors with series of functionally interdependent traffic controls, in contrast to isolated intersections.

Thus, the main objectives of this research are:

First Objective – To address the effect of the design features of roundabout corridors on traffic delay, CO_2, carbon monoxide (CO), nitrogen oxides (NO_X) and HC emissions.

Second Objective – To understand the differences in the spatial distribution of emissions between roundabouts in isolation and along corridors.

Third Objective – To compare traffic delay and emissions for corridors with different forms of intersections under different traffic and pedestrian volumes.

Fourth Objective – To improve the efficiency of corridors in terms of traffic performance, emissions and safety for pedestrians by designing of different features such as spacing between intersections, crosswalk locations and intersection layout.

1.3. Research Contributions

This Doctoral Thesis aims at assessing the impact of the different segments of each pair of roundabouts along corridors on traffic performance and vehicular emissions. The development of a methodology that incorporates geometric characteristics of the corridor and traffic stream on an integrated way is also a contribution of this work. The research herein will allow for solid knowledge in this topic by including a more extensive analysis, different case studies, intersection layouts, and traffic demand scenarios. This would help local authorities in decision-making process in the domain of mobility, emissions and safety.

Considering the identified gaps in the literature, namely the lack of a decision support methodology at the corridor level, an empirical component will be integrated with simulation models and optimization tools. The integration of different areas on those uninterrupted flow facilities is worthy of research at this stage.

The first novelty of this doctoral research is the assessment of the impact of roundabout corridors on traffic performance, energy, emissions and safety as pedestrian point of view. The design features that contribute to the spatial emissions distributions along roundabouts corridors are hypothesized to be different from roundabouts in isolation.

The second novelty is the use of microscopic simulation platforms of traffic, emissions and safety paired with a multi-objective analysis to compare the emissions and capacity performance of corridors with different traffic controls (conventional single and multi-lane roundabouts, turbo-roundabouts, traffic lights and stop-controlled intersections).

The third novelty is the identification of a trade-off among outputs regarding traffic performance parameters (delay), emissions (CO_2, CO, NO_X, and HC), and pedestrian safety (relative difference between pedestrian and vehicle speed).

The fourth novelty is the establishment of a relationship between those measures and the design features of corridors (spacing between intersections), pedestrian facilities (crosswalk location) or traffic flow characteristics.

1.4. Background

1.4.1. Categories of Roundabouts

A roundabout is a form of one-way circular intersection where vehicles circulate around a central island, and approaching traffic must yield to circulating traffic. The first traffic circle concept was introduced in 1877 by Eugene Henard (35). Large circular places were one of most pronounced elements of urban design in the 19th century. With increasing urban traffic at the beginning of the 20th century, these locations were the first where roundabouts were implemented such as Place Etoile in Paris (1907) or Columbus Circle in New York (1905). This trend has prompted the deployment of roundabouts worldwide (36).

The old traffic circles built in the US proved to be inefficient for three main reasons: *1*) yielding to entering traffic; *2*) tangential entries; and *3*) huge inner circle islands allowing long weaving distances. Yet, high crash experience and congestion levels in traffic circles led to rotaries falling out of favor in North-America after the mid-1950s (37). To rectify these problems, the modern roundabout was developed in the United Kingdom (UK), in 1966. The "off-site priority" rule was introduced to govern roundabout operations. This rule had two main concepts: *1*) entering traffic must give the way, or yield to the circulating traffic; and *2*) vehicles travelling further outside are not privileged in a conflict over the vehicles on the inner lanes. This concept yielded great success of roundabouts in the UK which led to an increase in capacity (38).

The styles of roundabout design vary by country (36). Brilon separates roundabouts into six basic categories (**Figure 1.3**) according to size, traffic flow and number of lanes (39):

- **Mini-roundabouts** are small roundabouts with a fully traversable central island, and a diameter between 13 and 23 m. They are commonly used in low-speed urban environments with average operating speeds of 50 km/h or less. They could carry up to 17,000 vpd;
- **Single-lane roundabouts** with a diameter between 26 (minimum required for heavy duty vehicles to make a full turn) and 35-40 m, with single-lane entries and exits only. The typical daily service is approximately 25,000 vpd;
- **Compact two-lane roundabouts** with inscribed circle diameters vary from 40 to 60 m, lane widths between 8 and 10 m, single or two-lane entries, only single-lane exits, and a maximum capacity of 32,000 vpd;

- **Conventional multi-lane roundabouts** provide two-lane entries and exits, and typical inscribed diameters ranging from 46 to 91 m. These roundabouts can handle between 35,000 and 40,000 vpd;
- **Turbo-roundabouts** with one or two segments in the circulating area. The ring carriageway contains continuous spiral paths in which the entry, the circulating, and the exit lanes are separated by raised curbs. Turbo-roundabouts are capable to carry up to 35,000 vpd depending on the arrangements of lanes at the entries and exits;
- **Signalized roundabouts** are suitable solutions for larger traffic volumes (they can handle between 50,000 and 60,000 vpd on a two-lane roundabout with a diameter higher than 50 m) (36, 39).

Figure 1.3 Categories of roundabouts: a) Mini-roundabout: b) Single-lane; c) Compact two-lane; d) Multi-lane roundabout; e) Turbo-roundabout; f) Signalized roundabout.

This is the classification used in Germany and in some European countries. Neither German guidelines nor local authorities adopt conventional multi-lane roundabouts in Germany due to high number of non-severe crashes (36). The Dutch government no longer constructs such roundabout layout, having adopted turbo-roundabouts as their current practice (40).

It must be emphasized that some of the aforementioned categories have not been explicitly identified for urban and rural areas. Roundabouts in urban areas may require smaller inscribed circle diameters because of the smaller design vehicles lower speeds, and some land use restrictions. They may also include pedestrians and bicycle facilities. Roundabouts in rural environments usually have higher approach speeds and therefore specific visibility and approach alignment concerns, and cross-sectional details changes (36, 37).

1.4.2. Roundabouts characteristics at isolated intersections

Roundabout installation has increased in the past few decades as a traffic control option at intersections in many countries. Currently there are approximately 2,800 roundabouts across the US (41). In Spain more than 30,000 roundabouts have been implemented in the last 20 years (42), and Germany had more than 12,000 roundabouts in 2014 (36).

In the next sections, roundabout characteristics pertaining to capacity, environment and safety are summarized.

1.4.2.1. Capacity

Operational analysis of individual roundabouts has been mostly conducted using methodologies and software from the UK (43), Australia (44) and the US (38). Most the existing roundabout capacity models rely on three methodologies: empirical models, gap acceptance models and microscopic simulation models. Albeit appropriate, any of above methodologies is able to fully describe the complex behavioral and physical processes involved in roundabout approaching movements (45).

Empirical models use statistical multivariate regression analyses to fit mathematical relationships between entry and circulating traffic flows, and other variables with impact on capacity. The drawbacks of this approach are the statistical and sampling constraints, namely: *a*) roundabout design such as size of the legs or orientations; *b*) reduced transferability among case studies; *c*) inclusion of oversaturated traffic flow conditions; and *d*) large amount of data to calibrate (45). The LR942 Linear Regression Model and based on Neural Networks are some of the well-known empirical regression models (45).

Gap acceptance models are focused on theoretical models developed from headway distributions between circulating and entering vehicles as well as in the usefulness of these gaps to the approaching vehicles. The data for these methods are thus less dependent on heavily congested entries with continuous queuing. Three variables are normally used to estimate entry capacity: *1*) critical gap (minimum time headway in the circulating stream that an entering driver will accept); *2*) follow-on headway (time headway between two consecutive queued vehicles entering the same gap in the circulating stream); and *3*) distribution of gaps in the circulating flow. These models lack good relationships between design features and capacity, and cannot be measured directly in the field. There are many formulations of critical gap distributions, such as Cowan's M3 parameter distributions, Wu's method, and Logit procedure. The main differences among these models are regarding the assumption of headway distributions and in the formulation of the input parameters (45).

Stochastic microscopic simulation provides good flexibility in the assessment of capacity models in roundabouts. Vehicle movements are governed by gap acceptance, car-following and lane-change driving behavior models, which are calculated for each vehicle at every specified time-step (45). Driver behavior parameters as critical gaps, and processes as vehicle generations are stochastically assigned through Monte Carlo methods using specified probability distributions. The validation and reliability of these models depend on an accurate representation of vehicle-vehicle interactions which can be difficult to replicate, even using observed data (45).

A plethora of traffic microscopic models is available for modelling roundabouts. These include S-PARAMICS (*PARAllel MICroscopic traffic Simulator)* (46), AIMSUN (*Advanced Interactive Microscopic Simulator for Urban and Non-Urban Networks*) (47) or VISSIM (*Verkehr In Städten – SIMulationsmodell*) (48). One of the limitations of microscopic simulation is the priority process at roundabouts. The gap-acceptance algorithms in microscopic traffic models are simplistic, usually under-predicting entry capacities in highly-congested levels, and inaccurately modelling driving behavior at multi-lane entries (45). Specifically, microscopic simulation models produce high entry capacity for the nearside entry lane as it only conflicts with the outer circulating lane rather than both circulating lanes. However, this does not occur in practice (vehicles in the nearside lane do not enter when there is a circulating vehicle on the inner lane) (49).

1.4.2.2. Emissions

The environmental benefits of roundabouts are not consensual, especially when compared to other forms of intersections. **Table 1.1** documents the most relevant environmental studies in two main groups: the first used only field data with an emission model (*1-7*); the second group included microscopic-mesoscopic traffic tool and an emission model (*8-15*). Macroscopic models are not suitable for roundabout environmental analysis since emission rates are constant for all speed ranges or they discarded stop and go cycles effects. On the other hand, microscopic models (e.g., Vehicle Specific Power – VSP) provide accurate emissions estimates during phases of accelerations or decelerations and speeds at high levels of resolution (1 s or less).

While some studies indicated reductions (50-53) in fuel consumption and emissions when using a roundabout over a traffic signal, all way stop control (AWSC) or two-way stop control (TWSC), other concluded that roundabout was a worse option than these traditional solutions (54, 55). Many authors recognized that the relative environmental and energy performance of roundabouts was dependent on its geometric and traffic stream characteristics (56-61). For instance, Salamati et al. showed that roundabouts produced lower emissions than traffic lights under low demand-to-capacity ratios ($d/c < 0.7$), but generated more emissions near saturation (57). Vlahos et al. found that roundabout generated lower emissions than traffic signal for d/c ranged from 1.0 to 1.3, and considering an Average Annual Daily Traffic (AADT) between 16,350 and 14,000 (58). According to research of Rakha and Jackson, single-lane roundabout produced fewer emissions than AWSC, TWSC, and traffic lights solutions under low traffic demands (≈500 vehicles per hour per approach or lower) (59). The study also implied for over-saturated conditions, traffic signals did not necessarily perform worse than roundabout.

Table 1.1 Key studies on the impact of isolated roundabouts operation on vehicular emissions

	Authors	Year	Methodology	Outputs	Limitations
1.	**Varhelyi (50)**	2002	Emission and fuel consumption factors for different levels of speed and two types of passenger cars: 1) petrol-driven without catalytic purifier; 2) petrol-driven with catalytic purifier	Average speed; delay; CO and NO_X emissions; fuel consumption	Emission rates based in dynamometer testing of vehicles, and valid within limited intervals of speed and acceleration. Emission and fuel consumption factors were only available for petrol-driven passenger cars.
2.	**Coelho et al. (60)**	2006	Emissions modeling using VSP with congestion-specific vehicle speed profiles	CO_2, CO, NO_X and HC emissions; entry and conflict traffic flows	Measurements were taken in two single lane roundabouts. Emissions estimation for Light Duty Gasoline Vehicles (LDGV) only.
3.	**Salamati et al. (61)**	2013	Emissions modeling using VSP with congestion-specific vehicle speed profiles	CO_2, CO, NO_X and HC emissions; entry and conflict traffic flows	Limited data sample of the studied multi-lane roundabouts. Emissions estimation for LDGV only.
4.	**Anya et al. (56)**	2013	On-board emissions monitoring an instrumented vehicle	NO, HC, CO and CO_2 emissions; travel time	Emissions assessment based on a vehicle basis. Only one site was considered.
5.	**Lima et al. (62)**	2013	Emissions modeling using Comprehensive Modal Emissions Model (CNEM) and CO dispersion modelling using Environmental Protection Agency Recommended Intersection Dispersion Model (CAL3QHC)	CO concentration	Emissions estimation for Light Duty Vehicles (LDV). Measurements in a specific roundabout.
6.	**Mudgal et al. (63)**	2014	Emissions modeling using VSP with speed profiles of drivers modeled by a Bayesian hierarchical regression mode	CO_2, CO, NO_X and HC emissions; acceleration profiles	Emission factors were from relatively ancient passenger cars.
7.	**Salamati et al. (57)**	2015	Emissions modeling using VSP with approximately 2,000 second-by-second speed trajectories from 24 roundabouts and 42 signalized intersections	CO_2, CO, NO_X and HC emissions	The methodology only separates roundabouts in low speeds (speed limit < 35 miles per hour – mph) and high speeds (speed limit > 35 mph.

	Authors	Year	Methodology	Outputs	Limitations
8.	**Vlahos et al. (58)**	2008	Emissions modeling using aaSIDRA	Delay, queue, CO_2, CO, NO_X and HC emissions	Limitations of emissions calculation with aaSIDRA (does not take into account the effect of stop and go situations). Limited sample size of roundabouts.
9.	**Mandavilli et al. (51)**	2008	Emissions modeling using aaSIDRA	Singular vehicle speed profiles (acceleration, deceleration, idling and cruising speed); CO_2, CO, NO_X and HC emissions	Limitations of emissions calculation with aaSIDRA (does not take into account the effect of stop and go cycles). One specific roundabout was analyzed.
10.	**Ahn et al. (54)**	2009	Microscopic traffic simulation (VISSIM) and INTEGRATION software in conjunction with VT-Micro (Virginia Tech Microscopic Energy and Emission) and CNEM emission models	Travel time; queue length; delay; intersection stops; fuel consumption; CO_2, CO, NO_X and HC emissions	Limited set of approach speeds and vehicles characteristics.
11.	**Chamberlin et al. (55)**	2010	Microscopic traffic simulation (PARAMICS) with MOtor Vehicle Emission Simulator (MOVES) and CNEM emission models	CO_2 and NO_X emissions	The evaluation was conducted in a virtual network.
12.	**Rakha and Jackson (59)**	2011	Simulation software INTEGRATION (includes VT-Micro for emissions modeling)	CO_2, CO, NO_X and HC emissions; fuel consumption	The research dealt with a very specific geometry and speed ranges of roundabout.
13.	**Rakha et al. (64)**	2012	Simulation software INTEGRATION (includes VT-Micro for emissions modeling)	Delay; CO_2, CO, NO_X and HC emissions; fuel consumption; vehicle stops	A unique set approach speed of 40 km/h and a 25 m radius roundabout was used.
14.	**Al-Ghandour (52)**	2014	Emissions modeling using aaSIDRA and MOVES	CO_2 and CO emissions; delay	Emissions estimation in single-lane roundabouts with one approach slip lane, under yield and free-flow exit control scenarios.
15.	**Gastaldi et al. (53)**	2014	Microscopic traffic simulation (PARAMICS) and AIRE (Analysis of Instantaneous Road Emissions)	NO_X, Particulate Matter of less than 10µm (PM_{10}) and total carbon emissions	Measurements in a specific roundabout.

1.4.2.3. Safety

Crashes at roundabouts accounted for 46 fatalities in the US between 2005 and 2013 (21 involved motorcycles) (65) while in the 28 European Union countries (EU28) they claim 257 lives (about 1% of intersection-related fatalities) in 2014 (66).

Roundabouts are a proven traffic control option for improving intersection safety by reducing conflict occurrence and crash severity, and forcing drivers to slow down as they approach through intersections and steering laterally around the central island (37). Roundabouts also eliminate the need for unprotected left-hand turns (67) and have less potential vehicle-to-vehicle conflicts points compared with four-way signalized intersections (68). Rodegerdts et al. (37) highlight the reasons that roundabouts increase safety levels: *1*) roundabouts have fewer traffic conflict points than conventional intersections, especially those which are most severe (e.g. right angle and left-turn head-on crashes); *2*) since roundabouts induce low speeds, drivers have long times to react to potential conflicts; and *3*) since most road users drive at similar speeds through roundabouts, crash severity can be reduced (37).

The current research on road safety has shown that roundabouts are safer than traditional stop sign or signal-controlled intersections (37, 38, 69-71). The most up-to-date information on the safety effects of 55 modern roundabouts in the US reports a 35% reduction in total crashes and a 76% reduction in injury crashes following conversion to a roundabout (38). Using crash data from Oregon, Dixon and Zheng found that roundabout was the safest solution under traffic demand lower than 30,000 vpd (71). Underline-Jensen evaluated 332 sites where roundabouts replaced traditional intersections from 1995 to 2009 in Denmark. The results showed a decrease in 60% in injuries after roundabout implementation, and that the reduction in crash frequencies were more noticeable in single-lane roundabouts than in the multi-lane layout (36).

In relation to research in bicycling mode in roundabouts, all studies highlight the fact that cyclists at roundabouts constitute a specific problem (36, 37). In 2014, 39 cyclists died after crashing at roundabouts in EU28 countries (about 2% of the cyclist-intersection fatalities) (72). An important consideration for cyclist safety is the evidence that motor vehicle drivers primarily look for other motor vehicles and therefore sometimes fail the visualization of cyclists (73). Despite the cycling safety improvements at roundabouts, these are not as relevant as for car passengers or pedestrians. Typical on-road bicyclist speeds are 19 to 32 km/h (37), so designing roundabouts for traffic circulating at similar speeds will reduce the relative difference between vehicles and bicycles speeds, thereby improving cyclist's safety.

There are different views on the safety benefits of spatial cycle facilities at single and multi-lane roundabouts, such as painted cycle lanes, separated cycle crossings and no cycle facilities. For single lanes, the adoption of mixed vehicles and bicycles roads is recommended up to a traffic flow of 15,000 vpd while a bicycling lane on the outer margin of the circular roadway must be avoided. The use of separated cycle crossings seems to be the safest option under high traffic flows (more precisely the crossings of the exits and the entries must be separated from the circle by 4 m) (37, 73). At multilane roundabouts, cyclists cannot be allowed on the same roadway as motor vehicles, and the use of tunnels and bridges are recommended. Separate cycle facilities must be precluded in the case of mini-roundabout (37).

Roundabouts have shown to result safer for pedestrians than for cyclists (73). For pedestrians, the risk of being involved in a severe collision is lower at roundabouts than at other forms of intersections mostly due to low vehicle speeds (38). Another advantage of roundabout is that it allows pedestrians to cross one direction of traffic at a time. This is considerably simpler than two-way stop-controlled intersections where pedestrians cross parallel with the major arterial and face potential conflicts (both in front and behind them). Nevertheless, pedestrians with vision impairments may have trouble finding crosswalks and determining if vehicles have yielded at crosswalks (38,74).

Some design manuals suggest locating the crosswalks 10 to 15 m downstream of the roundabout exit ring to avoid affecting traffic flow in the circulatory ring and simultaneously assuring pedestrian safety (75, 76). Undoubtedly, speed plays a significant role in whether a vehicle–pedestrian crash will result in a fatality. The change of pedestrian death caused by a vehicle increases from 5% to 40% if the vehicle speed increases from 32 to 50 km/h (37).

The available data of pedestrian crashes at roundabouts are very scarce. According to the 2014 statistics of European Commission (EC) approximately 20% of junction fatalities involved pedestrians (77). One of the first studies in pedestrian safety at roundabouts was performed by Haycock and Hall in 1984. It was found that pedestrians injury crashes decreased more than 50% when roundabouts were installed at existing UK intersections (78). In the Netherlands, a study conducted in 181 intersections showed a decrease in all pedestrian crashes by 73% after roundabouts implementation. Recent accident analysis study at urban single-lane roundabouts was published in Germany in 2012. The analysis confirmed the high degree of safety for pedestrians (5 severely injured persons and 11 slight injuries) (36). Pedestrian safety at roundabouts has attracted increased attention by scientific community (79-81). NCHRP report 674 (81) provides specific recommendations for the implementation of roundabouts to increase pedestrian safety. The report states that single-lane design should encourage low vehicle speeds near crosswalk, but it recognizes that this fact may represent a risk for blind pedestrians because traffic noise is low.

From the points discussed above the following conclusions can be drawn. The safety benefits of roundabouts were greater for small and medium capacity roundabouts than for large or multi-lane roundabouts (36-38), and for urban and suburban roundabouts that were previously two-way stop-controlled. Research is inconclusive, however, on the safety effect of roundabouts on the most vulnerable users such as cyclists and pedestrians.

1.4.3. Turbo-roundabouts as an alternative of conventional roundabouts

1.4.3.1. General Characteristics

Multi-lane roundabouts have specific safety concerns such as allowing vehicles to negotiate through the roundabout at high speeds and enabling lane changing and weaving maneuvers at the circulating and exit areas (82). Its design could also result in a trade-off between the safety of cyclists and pedestrians, and motor vehicles. At the single-lane roundabout, an increase in the vehicle path curvature reduces the frequency of crashes between vehicles, but in the multi-lane roundabouts, this potentially causes additional sideswipe collisions. Accordingly, designers face a dilemma: *1*) increasing vehicle path curvature that will result in more sideswipe collisions involving motor vehicles or *2*) decreasing vehicle path curvature that will provoke more severe crashes involving vulnerable users.

Thus, turbo-roundabouts have emerged as an alternative to conventional multi-lane layout since it solves a number of functional operational issues related to the latter layout, namely: *1*) it does not allow lane change at the circulating areas, and near the entry and exit areas; *2*) it induces low driving speeds near and through the roundabout because of the raised curb lane dividers; *3*) it reduces the number of conflict points by adding nested spiral lanes (40).

The Dutch manual identifies ten basic characteristics of turbo-roundabouts (**Figure 1.4**):

1) Nested spiral lane at one or more entries;
2) Yield to no more than two lanes;
3) Raised curb lane dividers;
4) Smooth spiral markings;
5) At least one lane offers a choice for direction;
6) Circulatory carriage kept narrow and deflected enough to maintain fastest speeds;
7) At least two exit legs have two exit lanes;
8) Perpendicular alignment between the circulatory lanes and entry legs;
9) Roundabout signage cuts off the horizon to increase the visibility;
10) Aprons in the central island to keep narrow lane width for passenger vehicles and provide additional surface for heavy duty vehicles (83).

Different types of roundabouts can be constructed on the basis of the principles specified above (83). Fortuijn firstly called one of such types "Basic Turbo-roundabout" (**Figure 1.4**) to distinguish it from other alternative designs.

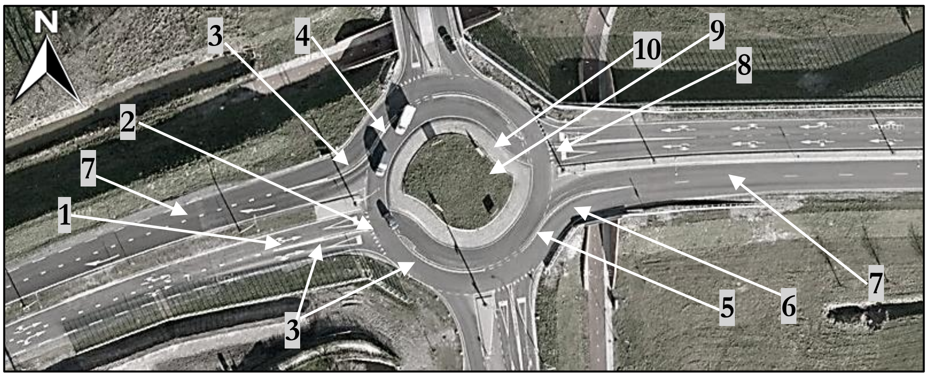

Figure 1.4 Basic turbo-roundabouts [Source https://www.google.pt/maps].

Types that lack features 5) and 7) are called as "Partial turbo roundabouts". Besides the "Basic Turbo-roundabout", different variants of the turbo roundabout are obtained by varying the number of lanes on the entry and the exit legs. The "Egg roundabout" has the unsystematic characteristic that the number of lanes in the side legs differs from that on the turbo-roundabout itself (**Figure 1.5**-a). The Knee solution (**Figure 1.5**-b) is adopted when high-left or high right-turning flows are presented. The Spiral layout (**Figure 1.5**-c) handles high traffic flows while the Rotor (**Figure 1.5**-d) is suitable for similar traffic distribution among legs (83, 84).

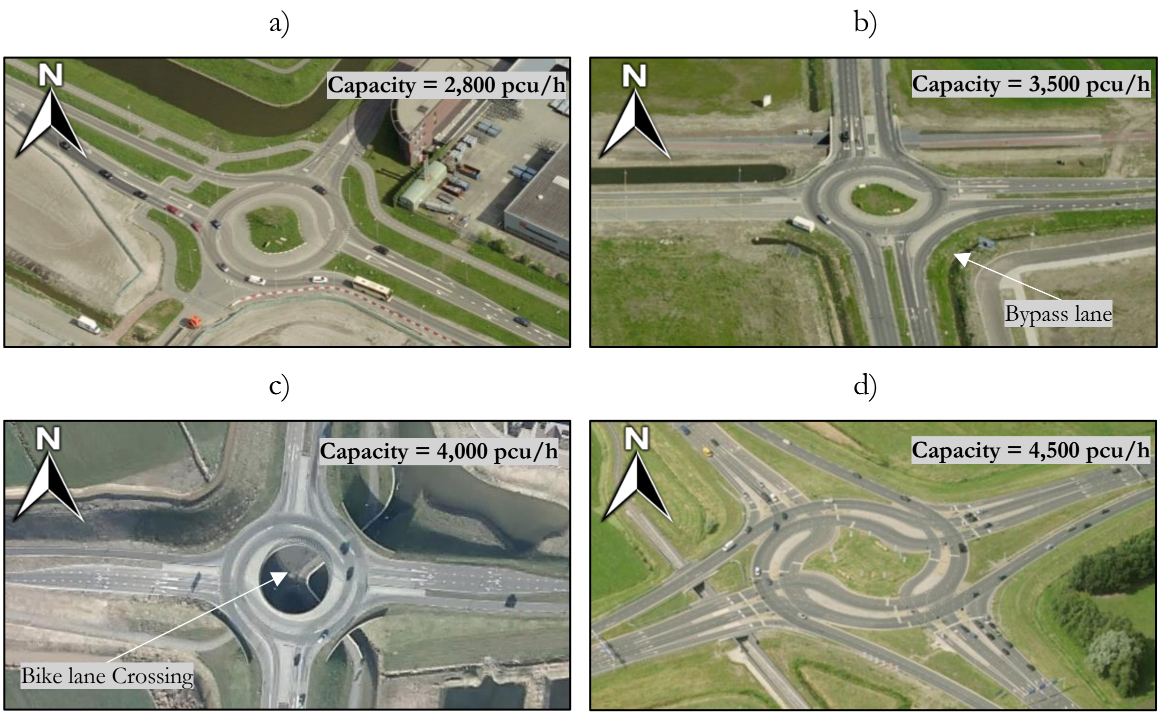

Figure 1.5 Turbo-roundabout layouts with by approximation the capacity (pcu – Passenger Car Unit) (6): (a) Egg; (b) Knee; (c) Spiral; and (d) Rotor [Source: http://www.bing.com/maps/].

1.4.3.2. Current research on turbo-roundabouts

Turbo-roundabouts have been growing in popularity in several European countries as Netherlands, Germany or Poland. Since the construction of the first turbo-roundabout in 1999, more than 400 turbo-roundabouts were adopted as a traffic control at intersections (85).

Albeit recent, turbo-roundabout has been extensively studied by the scientific community, especially in terms of safety and capacity purposes. Previous works have reached greater consensus concerning the safety benefits of turbo-roundabouts comparing with conventional multi-lane layouts (84, 86-89). In fact, the complete elimination of weaving and cut-in conflicts on a turbo-roundabout leads to a reduction in the number of conflict points [24 in two-lane roundabouts and 14 in turbo-roundabouts (90)]. Turbo-roundabout design also imposes low entry and circulating speeds, which can benefit some vulnerable users such as pedestrians and cyclists (91).

The research conducted on capacity has been raised some doubts about the effectiveness of turbo-roundabouts for traffic. First studies suggested higher capacity rates for turbo-roundabout than traditional multi-lane roundabouts (92, 93), however, their methodologies only considered very specific traffic demands. Most recent research done suggested that the entry and the conflicting traffic flows, directional split of traffic, pedestrian activity or driving habits widely influence the capacity of turbo-roundabouts (40, 89, 94-98).

Very little attention has been given to the emissions performance of turbo-roundabouts which, as a matter of fact, is a discriminating factor in choosing the most suitable intersection in urban areas (99). Vasconcelos et al. (90) compared emissions generated from vehicles as they drive through a turbo-roundabout, and conventional single and two-lane roundabouts. The results obtained were mixed: turbo-roundabouts produced more CO_2 and NO_X emissions than two-lane roundabouts; CO and HC were higher in two-lane roundabouts compared with turbo-roundabout.

1.5. Structure of the Thesis

This thesis comprises seven main chapters and its structure is explained as follows. **Chapters 2** to **6** are based on published and submitted manuscripts, as presented in **Table 1.2**.

Chapter 1 presents a general statement of the research problem, outlines the impact of different forms of intersections in isolation and along corridors on traffic performance, emissions and safety, and highlights the main gaps in this topic. The research objectives and contributions are presented. The thesis organization is also provided.

Chapter 2 investigates the impact of turbo-roundabouts in isolation on pollutant emissions using empirical data, and further compares their performance to conventional two-lane roundabouts (**Third Objective**). This chapter stresses the importance of identifying the potential of turbo-roundabouts located in urban corridors to enhance both capacity and emission impacts.

Chapter 3 introduces a methodology to quantify and characterize emissions at four urban roundabout corridors at the segment level, and identify the hotspot emissions locations (**First** and **Second Objectives**). This chapter highlights the importance of discerning the influence of design features on emissions at roundabouts in isolation and along corridors, thus providing relevant information for the research performed in the next chapters.

Given the impossibility of using only empirical data to design and reproduce alternative traffic scenarios, simulation platforms are then used to compare corridors with different forms of intersections in **Chapters 4** and **5** (**Third Objective**). A fundamental question addressed in **Chapter 4** is the assessment of the effects of a real-world roundabout corridor on traffic performance and pollutant emissions, in contrast with traffic lights and stop-controlled layouts. **Chapter 5** compares traffic performance, and global and local pollutant emissions between turbo-roundabout and conventional two-lane roundabout corridors. The main contribution of these chapters is the deeper analysis of geometric and operational characteristics of corridors with innovate layouts prior to their implementation in urban areas.

Chapter 6 focuses on the design optimization in corridors with closely-spaced conventional roundabouts (single-lane and multi-lane roundabouts) and traditional solutions (traffic lights and stop-controlled intersections) (**Fourth Objective**). This chapter is divided into three main sections. **Section 6.1** addresses the integrated effect of a pedestrian crosswalk on traffic delay, CO_2 emissions, and relative difference between vehicles and pedestrians speed at different locations on an urban corridor with two closely-spaced roundabouts. In **Section 6.2**, the multi-objective analysis of pedestrian crosswalk locations is extended to local pollutants (CO, NO_X and HC) and considering roundabout corridors located in Portugal, Spain and in the US. These studies contribute to the better understanding of spacing as a factor affecting optimal crosswalk location along a mid-block section. **Section 6.3** analyzes highly-congested closely-spaced intersections along an urban corridor to select the most suitable layout. The optimization of spacing between intersection to improve traffic performance and emissions also has conducted.

Chapter 7 summarizes the overall findings and main conclusions followed by a critical analysis of the research performed. This chapter finishes discussing possible future developments.

Table 1.2 Relationship between the structure of chapters and published/submitted articles

Chapter	Reference Paper
2	Fernandes, P, Pereira, SR, Bandeira, JM, Vasconcelos, L, Silva, AB, Coelho, MC. Driving around turbo-roundabouts vs. conventional roundabouts: Are there advantages regarding pollutant emissions? International Journal of Sustainable Transportation. 2016; 10(9): 847-860. DOI: http://dx.doi.org/10.1080/15568318.2016.1168497
3	Fernandes, P, Salamati, K, Rouphail, NM, Coelho, MC. Identification of Emission Hotspots in Roundabouts Corridors. Transportation Research Part D: Transport and Environment. 2015; 37: 48-64. DOI: http://dx.doi.org/10.1016/j.trd.2015.04.026
4	Fernandes, P, Fontes, T, Neves, M, Pereira, SR, Bandeira, JM, Coelho, MC, Rouphail, NM. Assessment of corridors with different types of intersections: An environmental and traffic performance analysis. Journal of Transportation Research Record: Journal of the Transportation Research Board, Transportation Research Board of the National Academies. 2015; 2503: 39-50. DOI: http://dx.doi.org/10.3141/2503-05
5	Fernandes, P, Rouphail, NM, Coelho, MC. Turbo-roundabouts along corridors: Analysis of operational and environmental impacts. Journal of Transportation Research Record: Journal of the Transportation Research Board, Transportation Research Board of the National Academies. 2017, in press.
6.1	Fernandes, P, Fontes, T, Pereira, SR, Coelho, MC, Rouphail, NM. Multicriteria assessment of crosswalk location in urban roundabout corridors. Journal of Transportation Research Record: Journal of the Transportation Research Board, Transportation Research Board of the National Academies. 2015; 2517: 37-47. DOI: http://dx.doi.org/10.3141/2517-05
6.2	Fernandes, P, Salamati, K, Coelho, MC, Rouphail, NM. The effect of a roundabout corridor's design on selecting the optimal crosswalk location: a multi-objective impact analysis assessment on the design for optimal crosswalk location. International Journal of Sustainable Transportation. 2017, 11(3): 206-220. DOI: http://dx.doi.org/10.1080/15568318.2016.1237689
6.3	Fernandes, P, Coelho, MC, Rouphail, NM. Assessing the impact of closely-spaced intersections on traffic operations and pollutant emissions on a corridor level. Submitted for publication in the Transportation Research Part-D: Transport and Environment. 2017.

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2 TURBO-ROUNDABOUT: A NOVEL DESIGN

The operational and safety analysis of innovative roundabout layouts as turbo-roundabouts is extensive. However, there are some doubts about their environmental benefits, especially when compared to the conventional multi-lane layout. Some specificities of turbo-roundabouts such as the existence of curb raised dividers that decrease vehicle speeds at circulating areas or less dedicated lanes for trough traffic may decrease turbo-roundabout emissions performance. Thus, this chapter evaluates and compares turbo-roundabouts and multi-lane roundabouts emissions based on the levels of congestion. The importance of this chapter based on a better knowledge concerning the potential implementation of turbo-roundabout on a corridor level.

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Abstract

This article addresses the impact of turbo-roundabouts located in urban areas on pollutant emissions using field measurements of vehicle activity data and road congestion levels. The research also compares the emissions of vehicles moving along a turbo-roundabout and a conventional multilane roundabout. Based on field measurements taken at turbo-roundabouts without curb dividers located in Grado, Spain, and multilane roundabouts in Aveiro, Portugal, three representative speed profiles for each speed trajectory were identified: no stop (I), stop once (II), and multiple stops (III). This study also develops discrete models for turbo-roundabouts and multilane roundabouts in which the relative occurrence of those speed profiles is expressed as a function of the entry and conflicting traffic flows. The vehicle specific power (VSP) methodology is then employed to estimate second-by-second pollutant emissions. This study tests the hypotheses that emissions are impacted by the differences in (a) the characteristics of speed profiles in each movement, (b) the volumes of entry and conflicting flows, (c) the overall saturation level, and (d) the transportation facility considered (turbo-roundabout / multilane roundabout). Considering the selected case studies and traffic demands, vehicles at turbo-roundabouts generated more emissions (15–22%, depending on the pollutant) than multilane conventional roundabouts, especially under medium and high congestion levels. These findings suggest that there are no advantages in implementing turbo-roundabouts from an environmental point of view regardless of the traffic congestion levels.

Keywords: Turbo-roundabouts; Multi-lane roundabouts; Speed Profiles; Discrete Models; Emissions.

2.1. Introduction and Research Objectives

Multi-lane roundabouts can handle larger volumes of traffic than single-lane roundabouts. However, they have some drawbacks such as allowing vehicles to negotiate the roundabout at higher speeds and enabling lane changing and weaving maneuvers at the circulatory ring and exit areas, leading to higher traffic conflicts (1).

The turbo-roundabout concept was developed to address these problems, as an alternative of the conventional multi-lane roundabouts where drivers are required to choose their intended destination before entering the roundabout. The ring carriageway contains continuous spiral paths in which the entry, the circulating and the exit lanes are usually separated by curbs. Such raised curbs eliminate the conflicting points caused by weaving maneuvers and control the vehicle speeds (2). The first turbo-roundabouts were constructed in the Netherlands, in 2000 (3, 4). Since then, turbo-roundabouts have been increasingly used in several European countries including Germany (5), Slovenia (6, 7), and most recently in Spain (8). Awareness about this layout is also growing in the United States (US) (9) and Italy. Their design features are usually based on the Dutch guidelines (3, 4).

In Portugal, roundabouts have gained in popularity and are now widely used to control traffic at intersections. They enjoy good levels of popular and political acceptance. However, the lack of technical and legal regulations specifically applicable to roundabouts has led to a significant number of crashes, especially in the multi-lane layout. The above findings have led to the development of some innovative design solutions, as is the case of the turbo-roundabout concept. Thus, it is important to understand the real performance of the turbo-roundabout at distinct levels, whose benefits are still uncertain, especially in terms of vehicular emissions.

A typical concern with the use of turbo-roundabouts is their impact in terms of capacity. **Figure 2.1** illustrates a conventional roundabout (four double-lane entrances and four double-lane exits) and a turbo-roundabout of similar size (four double-lane entrances, two double-lane exits and two single-lane exits). The turbo-roundabout was aligned assuming direction AC as a major direction, and provides two entry lanes for these movements. The main differences that affect capacity are (2):

- On a conventional roundabout, the outer circulatory lane at the major entrances (A and C) is used by a fraction of the through movements (DB and BD); on a turbo-roundabout, the opposing traffic is concentrated in a single lane, which reduces the frequency of large gaps and leads to a decrease in capacity;
- On a conventional roundabout, drivers in the outer lane (adjacent to the sidewalk) of the minor entrances (B and D) are affected by all circulating vehicles, even if the trajectories do not actually intersect; on a turbo-roundabout, the outer lane is used only for right-turn (BC and DA movements) and the opposing traffic is reduced since part of the through traffic is physically separated at the exit;
- While right-turning traffic must use the outer entry lane on the conventional roundabout (BC and DA movements), both the inner and outer lanes can be used at the minor entrances of a turbo-roundabout.

The differences in layouts are also reflected in vehicle speeds. The spiral lanes associated with raised dividers define high curvature paths, forcing a slow approach and circulating speeds.

These design considerations have a significant effect on intersection capacity and can also affect pollutant emissions.

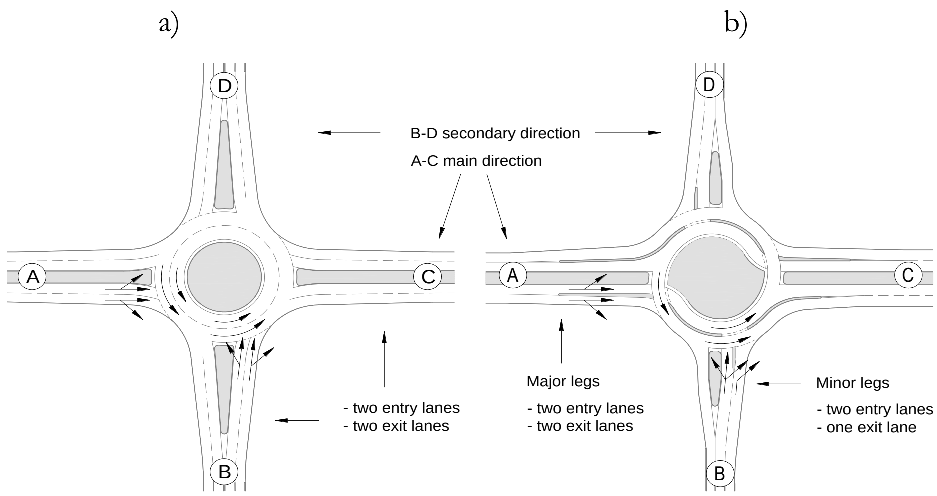


Figure 2.1 Differences between roundabout layouts: a) Multi-lane roundabout; b) Turbo-roundabout.

This work introduces a methodology that can explore the effect of turbo-roundabout operations on pollutant emissions and capacity. The methodology described in this study is built on previous studies (10, 11) which were dedicated to the environmental impacts of conventional single (10) and multi-lane roundabouts (11). It is hypothesized that emissions and capacity are impacted by the differences in: *1*) the characteristics of the speed profiles; *2*) the volumes of entry and conflicting flows; *3*) the overall saturation level; and *4*) the adopted layout (multi-lane versus turbo-roundabout). The research uses an approach founded on experimental measurements of traffic characteristics and saturation levels in real turbo-roundabouts to predict the relative occurrence of each speed profile that vehicles experience as they travel through the turbo-roundabout. These speed profiles are: no stop (I), stop once (II) and multiple stops (III) at the entry of the turbo-roundabout. Emissions are then estimated using the Vehicle Specific Power (VSP) methodology (12), which is based on on-board measurements in Light Passenger Vehicles (LPV).

The occurrence of the speed profiles (I, II and III) was calculated by employing discrete choice models which are used for modeling the chosen experimental data. These models are widely used in transportation problems to study both revealed and stated preference data. Using the models developed, it is possible to estimate the footprint of emissions at any turbo-roundabout, knowing the entry and conflicting flows and by identifying the typical speed profile for each trajectory. Thus, the objectives of this research are threefold:

- To quantify emissions generated by vehicles at roundabouts (turbo-roundabout and multi-lane layouts) located in urban areas;
- To develop appropriate models to explain the interaction between operational variables (entry and conflicting traffic flows) and the main geometric characteristics of a turbo-roundabout;

- To compare the emissions and capacity impacts of turbo-roundabouts with those of multi-lane roundabouts.

Section 2.2 presents a review of the technical literature. The methodology used in this research is explained in **Section 2.3**. Results are presented and discussed in **Section 2.4**, followed by the main conclusions and research limitations in **Section 2.5**.

2.2. Literature Review

Previous studies in the field of transportation capacity, safety and emissions have dealt with the impacts of turbo-roundabouts on traffic operations and compared them with conventional single-lane and two-lane roundabouts.

From the literature, it is clear that there is still no consensus about the benefits of turbo-roundabouts regarding the available capacity of the intersection. The first studies carried out (13, 14) showed that turbo-roundabouts achieved higher capacity than traditional roundabouts with similar design features. Other authors (15-18) recognized that the relative performance of turbo-roundabouts was largely dependent on the local traffic conditions and layout. Corriere and Guerrieri (19) explain that, for each site, the pedestrian presence, conflicting traffic flows, lane capacity, driver behavior, balance of the traffic demand on each approach, and the traffic flow balance at the circulating lanes will affect each approach capacity and vehicle delay at turbo-roundabouts. Vasconcelos et al. (20) proposed a new lane-based capacity methodology to assess the capacity of a turbo-roundabout based on gap-acceptance theory. The authors stated that the turbo-roundabout only achieved capacity levels comparable to the traditional two-lane layout when the proportion of right turns at the minor entrances was very high.

However, the safety benefits of turbo-roundabouts are consensual in almost all previous studies confirming their advantages over the multi-lane layout (2, 18, 21).

Although extensive, the current macroscopic (e.g. Computer Programme for calculating emissions for Road Traffic – COPERT or Transport Emission Model for Line Source – TREM), mesoscopic (e.g. aaTraffic Signalized and unsignalized Intersection Design and Research Aid – aaSIDRA) and microscopic emission models (e.g. Virginia Tech Microscopic Energy and Emission – VT-MICRO, Comprehensive Modal Emissions Model – CMEM, VSP, MOtor Vehicle Emission Simulator – MOVES) have limited applications in roundabout case studies. TREM and COPERT are not suitable for microscale impacts estimation of roundabouts since they assume that emission rates are constant for different speed ranges (22, 23). aaSIDRA contains vehicle emissions estimates based on a "four-mode elemental model": deceleration, idle, acceleration and cruise, but it does not include the impact of stop and go cycles (24).

Alternatively, microscopic models estimate instantaneous vehicle fuel consumption and emission rates, which are aggregated to estimate network-wide measures of effectiveness. These models are sensitive to changes in vehicle acceleration behavior and thus can be used in the evaluation of operational-level transportation projects such as roundabouts. One widely used microscopic approach is the estimate of emissions through the concept of vehicle specific power (VSP). The on-board vehicle activity and emissions are acquired by a portable emissions measurement system (PEMS) that assesses emissions under real-world conditions at any location by vehicles on a second-by-second basis (25). VSP is highly correlated with emissions since it overcomes the fact that the cruise mode has a fixed factor independent of speed; it includes the impact of different levels of accelerations and speed changes on emissions; and it accounts for the effect of road infrastructure on power demand (26).

A good deal of research has documented the effective use of the VSP methodology to estimate the emissions of vehicles at different roundabout layouts (10, 11, 27-29). Coelho et al. (10) identified three characteristic of speed profiles for a vehicle approaching single-lane roundabouts: no stop (I); stop once (II) and multiple stops (III). They also found that the relative occurrence of these profiles was dependent on the entry and conflicting traffic flows. Based on these findings, the same authors developed regression models to describe the relative occurrence of these speed profiles for approaching vehicles at single-lane roundabouts. Based on this research, Salamati et al. (11) developed similar regression models in each approaching lane (right versus left) at multi-lane roundabouts. Anya et al. (27) explored the environmental benefits posed by the conversion of a signalized intersection into a two-lane roundabout in an urban corridor in Raleigh. They found that the implementation of the roundabout was only relevant at the intersection-level in the right turn movements from the minor street to the main street. Mudgal et al. (28) demonstrated that acceleration events in the circulating and exiting areas of a roundabout contributed to more than 25% of the emissions for a given speed profile.

The assessment of turbo-roundabouts with respect to certain impacts is relatively unknown. Vasconcelos et al. (29) used microsimulation models to evaluate and compare the performance of a single-lane roundabout, in Coimbra, Portugal, and modeled a two-lane roundabout and a turbo-roundabout in terms of capacity, safety and emissions. The results showed that the turbo-roundabout reached higher saturation levels and delays than two-lane roundabout, especially under high proportions of left turns (more than 60%). Concerning emissions, carbon dioxide (CO_2) and nitrogen oxides (NO_X) were higher for the turbo-roundabout, regardless of the proportion of turning movements and/or traffic flows at each approach. Tollazzi et al. (30) introduced a methodological framework to compare capacity and vehicle delays as well as CO_2, NO_X, and particulate matter of less than 2.5μm ($PM_{2.5}$) and 10μm (PM_{10}) at different roundabout layouts: target, four-flyer, flower and conventional. The authors found that under medium-high entry traffic volumes (~2,800-3,000 vehicles per hour – vph) the target roundabout offered lower costs than the other intersections. However, the analysis did not include field measurements of turbo-roundabouts.

The literature review indicates some gaps. First, the analysis of the turbo-roundabouts focused on their capacity and/or safety performance. Second, the characterization of speed profiles in turbo-roundabouts using field data has not been examined previously by other researchers. Third, there is a lack of emissions quantification at turbo-roundabouts, based on real traffic and vehicle dynamics measurements.

The novelty of this study is that it uses field data collected from real turbo-roundabouts (traffic flows and vehicle activity data) to estimate emissions. Moreover, it compares the emissions levels at turbo-roundabouts with those at the conventional multi-lane layout.

2.3. Methodology

This study is an empirical approach based on field measurements of the vehicle dynamics and the overall congestion level. The methodology overview is depicted in **Figure 2.2**. Input data such as entry and conflicting traffic flows, queue length and stop-and-go cycles were collected by overhead video cameras installed at the roundabouts (turbo-roundabouts and multi-lane roundabouts). Vehicle activity data such as second-by-second instantaneous speed, acceleration-deceleration and grade were collected using a Global Positioning System (GPS) data logger and On-Board Diagnostic (OBD) system. The relationship between congestion level of roundabouts and occurrence of each speed profile was then established, using discrete choice models (31). After that, the VSP methodology was used to estimate CO_2, carbon monoxide (CO), NO_X and hydrocarbons (HC) emissions. Finally, the discrete choice models obtained from turbo and multi-lane roundabouts were compared. The following sections describe the methodological steps in detail.

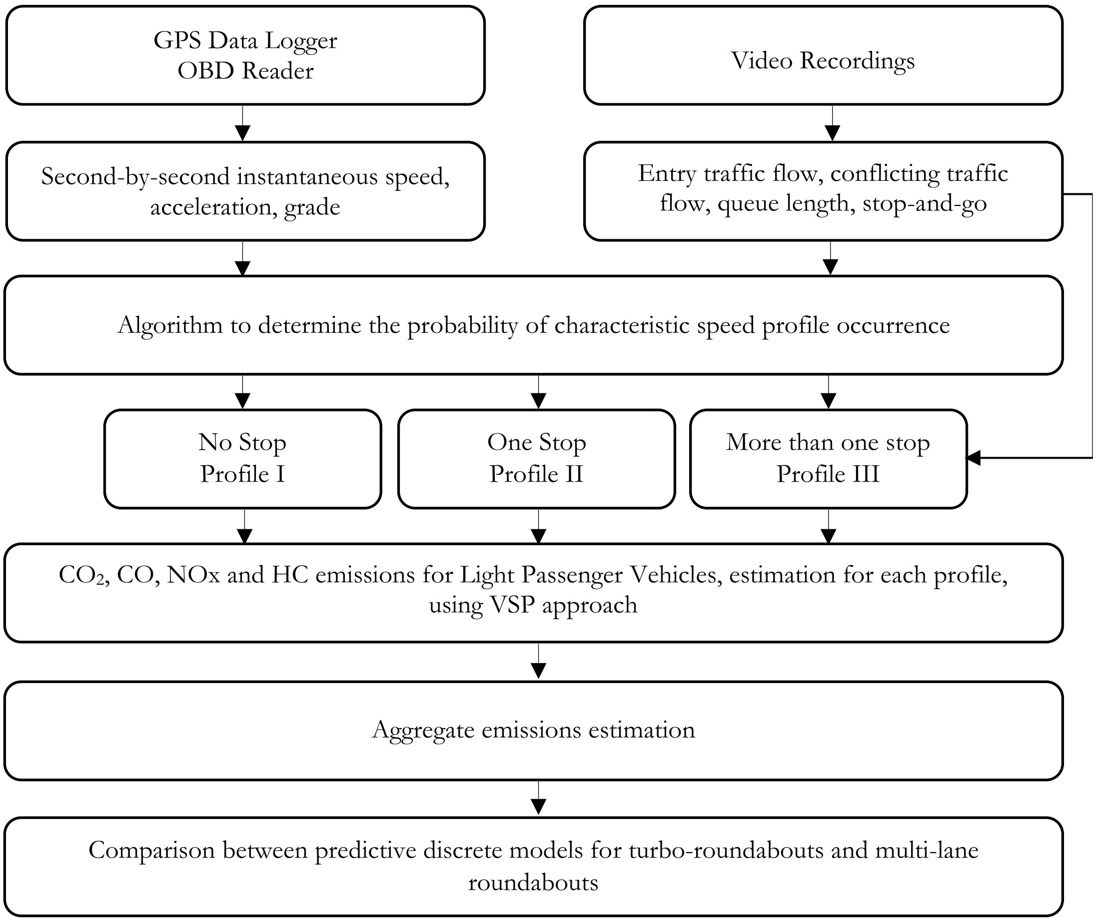


Figure 2.2 Methodology Overview.

2.3.1. Site Selection

Two sets of roundabouts were selected for this study – three multi-lane roundabouts and three turbo-roundabouts. **Figure 2.3** shows the aerial view of the data collection sites as well as the studied approaches. Three turbo-roundabouts on the N-634 national road in the city of Grado, Spain were selected (**Figure 2.3***a-c*). These turbo-roundabouts were selected because there are no layouts of this type in Portugal. Iberian case studies are therefore represented. These turbo-roundabouts were constructed and started operating in 2009 (8).

The through movement from the northeast-bound approach was studied using GPS and OBD runs in different directions. That approach has two entry lanes from 200 m to the yield line of the turbo-roundabout. The right lane only provides movements to the first exit while the left lane allows the remaining movements. The multi-lane roundabouts, displayed in **Figure 2.3** (*d-f*), are located in the urban area of Aveiro, Portugal, and have two entry lanes on their approaches and two circulating lanes.

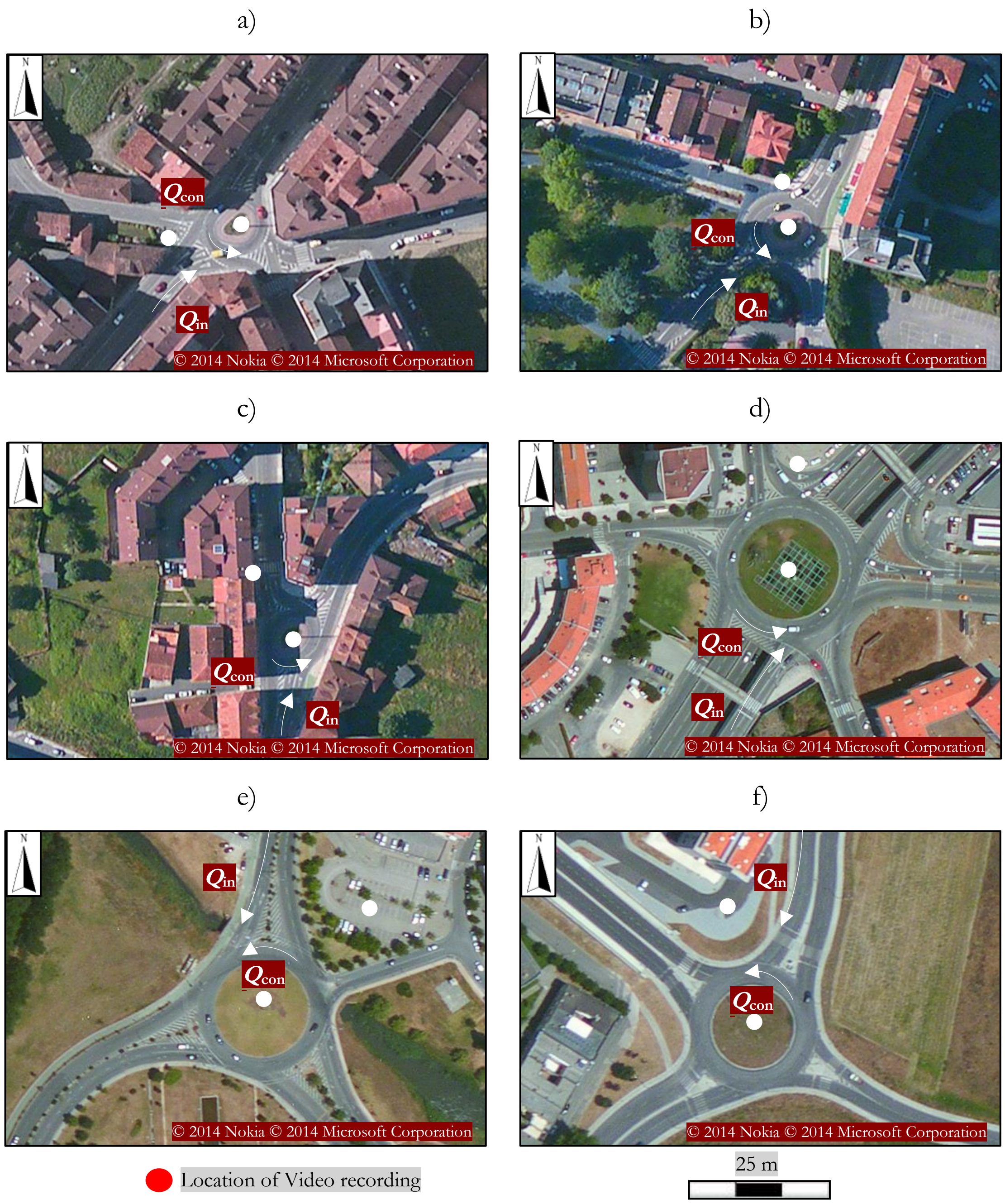


Figure 2.3 Aerial View of the three data collection turbo-roundabouts, Grado, Spain: a) TR1; b) TR2; c) TR3 and multi-lane roundabouts, Aveiro, Portugal: d) ML1; e) ML2; f) ML3.

The posted speed limit in the studied areas is 40 km/h. The sites' characteristics such as location, circulating width, the average approach speed, and the speeds at the entrance and exit lanes of the roundabouts are summarized in **Table 2.1**. The morning entry and conflicting traffic flows are also provided.

It should be mentioned that at the time of the field tests these turbo-roundabouts did not have a raised lane divider (only longitudinal double-line markings). However, almost every vehicle uses the inner and outer lanes correctly for their intended destination.

Table 2.1 Key Characteristics of Selected Corridor

ID	Approach Speed[a] (km/h)	Entry Speed[b] (km/h)	Exit Speed[b] (km/h)	Circulating Speed (km/h)	Circulating Width (m)	Entry Traffic[c] (vph)	Conflicting Traffic[d] (vph)
TR1	31.1	18.8	21.5	15.8	6.0	275	347
TR2	32.0	21.8	21.7	17.0	6.2	500	305
TR3	32.5	27.5	25.7	26.5	6.1	435	90
ML1	35.1	34.1	40.2	30.1	8.3	585	1,110
ML2	33.4	32.2	34.2	24.1	8.2	660	650
ML3	32.4	24.0	35.0	26.1	8.1	470	448

[a] *Average approach speed 150-200 m from the circulatory ring of the roundabout.*

[b] *Values observed at the entrance and exit lines.*

[c] *Average values of traffic flows (right and left lanes) observed for the morning peak period (8-9 a.m.).*

[d] *Average values of traffic flows (all circulating lanes) observed for the morning peak period (8-9 a.m.).*

2.3.2. Data Collection

This work applied field data collection techniques to find the traffic characteristics of the two roundabouts layouts. The research team surveyed and collected data at the roundabouts during the morning (8:00 – 11:00 a.m.) and afternoon (5:00 – 8:00 p.m.) peak periods on typical weekdays (Tuesday to Wednesday) in May, 2014. The following data were collected:

- Entry and conflicting traffic flows;
- Maximum queue length;
- Number of stop-and-go cycles;
- Vehicle activity data on a second-by-second basis (speed, acceleration-deceleration and grade).

The duration of the video recording was obtained using statistical significance tests to enable the estimation of a 95% confidence interval in relation to the average and standard deviation of the traffic stream parameters. Entry and conflicting traffic flows, queue lengths and the number of stop-and-go situations were recorded by overhead video cameras installed at two strategic points on the roundabouts, as illustrated in **Figure 2.3**. The first camera recorded all vehicle paths through the roundabouts; the second camera, which was installed on the central island, recorded the queue lengths at the selected entrances.

The estimated instantaneous speed and acceleration-deceleration profiles were derived from experimental data on vehicle dynamics using an LPV conforming to Euro V Emission Standard equipped with a GPS and OBD to make several turning movements at the roundabouts. The vehicle has the following characteristics: year – 2013; mileage – 5,700 km; engine size – 1.5L; maximum power – 81 kW at 4,000 rpm; torque – 1,750 rpm; transmission type – 5-speed manual gearbox; gross vehicle weight – 1,210 kg. These characteristics are within the tested LPV specifications that were used to obtain the emissions factors for VSP methodology. The test vehicle is also representative of the LPV category in Europe (32).

The QSTARZ GPS Travel Recorder (33) was used to capture second-by-second vehicle speed and the selected sites' characteristics (road grade, latitude and longitude). The CarChip Fleet Pro OBD sensor was used in coordination with the in-vehicle GPS to record the vehicle speed, distance travelled and deceleration-acceleration rates in 1-second intervals (34). To coordinate the equipment, the research team powered off the vehicle between travel movements to and from the roundabout (in locations outside the influence area of the study locations).

A total of 240 GPS travel runs of through movements (approximately 40 at each location) were identified and extracted for this research (approximately 400 km of road coverage over the course of 15 h). According to Li et al. (35), for a significance level of 5%, the above number of runs (sample size) per location was considered to be suitable to generate reliable results from the data acquired.

To reduce systematic errors, 3 drivers (all male, aged 25 to 35 with varying levels of driving experience) performed the same number of trips (approximately 40) for each roundabout movement. Concurrently, over 21 h of video data (total of 84 data samples of 15 min) were gathered from the six roundabout approaches (approximately 3.5 h at each location). These series of measurements were sufficient to enable the estimation of a 95% confidence interval in relation to the average and standard deviation of the measured parameters.

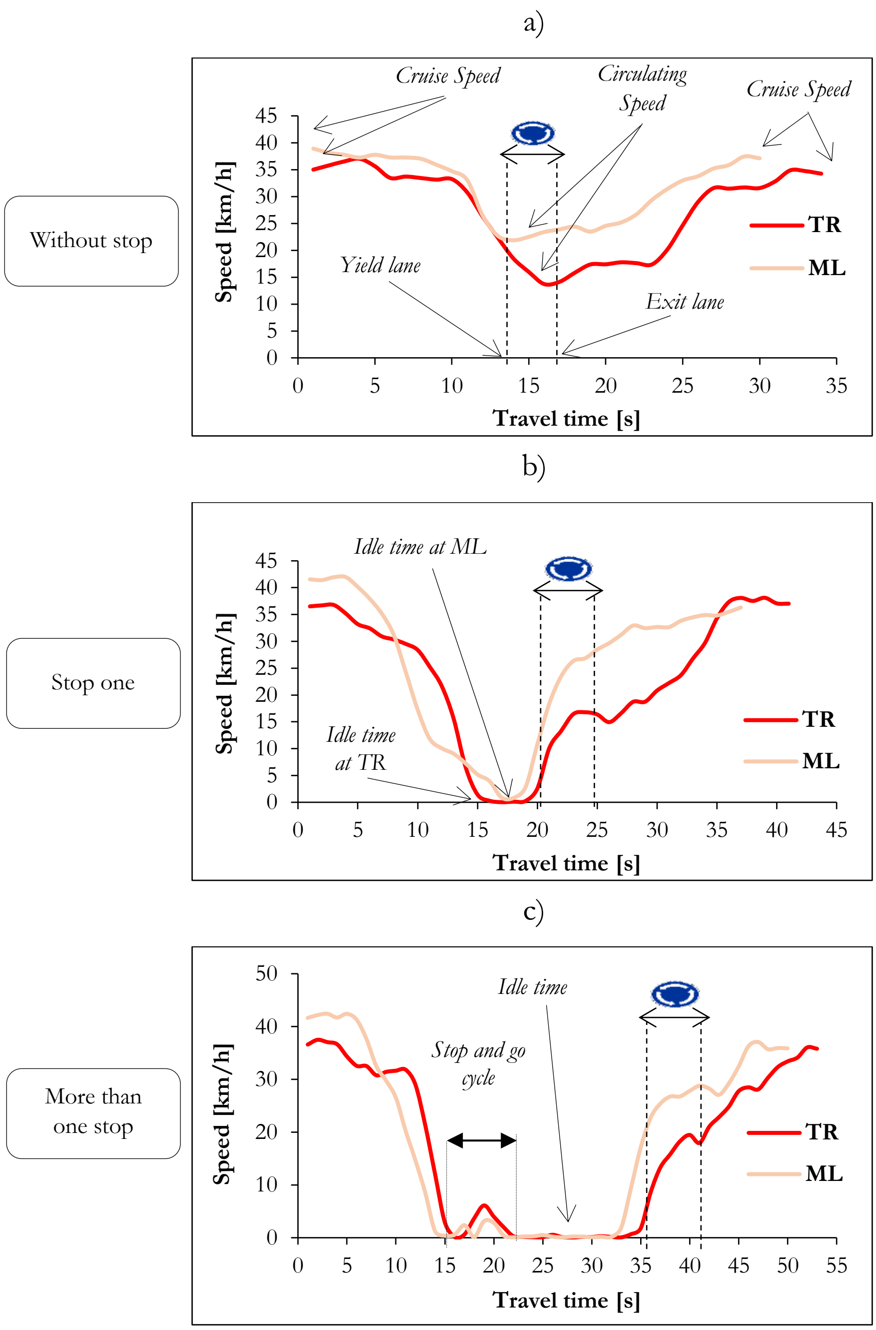
2.3.3. Characteristic Speed Profiles

Based on vehicle activity, and patterns in speed profiles, vehicles experience three different speed profiles (**Figure 2.4** *a-c*) as they approach a generic roundabout (multi-lane or turbo), as demonstrated by previous studies (10, 11). It should be noted that the relative occurrence of each profile is highly dependent on the level of congestion of the approach (10, 11). The three speed profiles represent:

I. A vehicle starting to decelerate while approaching the roundabout, enters and negotiates the circulating area without stopping and then accelerates back to cruise speed as it is leaving the roundabout;

II. A vehicle decelerates while approaching the roundabout, comes to a complete stop at the yield line to enter in the circulating stream and finds a crossable gap, then accelerates to enter the circulating ring and exits the roundabout;

III. A vehicle that experiences several stops on the approach as it moves up the queue to reach the yield line, and then accelerates to enter the circulating ring and leaves the roundabout.



Legend: TR – Turbo-Roundabout; ML – Multi-lane Roundabout

Figure 2.4 Example of typical speed profiles through turbo-roundabout and multi-lane roundabout (from the left entry lane): a) speed profile I; b) speed profile II and c) speed profile III.

The main goal of this research is to quantify the relationship between the congestion levels of the roundabouts and the percentage of vehicles that experience each speed profile. These levels of congestion are expressed indirectly as the sum of the entry (Q_{in}) and conflicting traffic flows (Q_{conf}) at each entry lane (10). Video cameras are used to capture the vehicle movements at the entry and circulating lanes of the selected roundabouts. Q_{in} and Q_{conf} are both obtained for every

15 min of morning and afternoon peak periods. The proportion of the drivers that do not stop at the entry (P_I), experience one complete stop (P_{II}) and multiple stopping (P_{III}) are also extracted from the recordings.

2.3.4. Discrete Choice Models

As mentioned before, the main goal of the proposed model is to identify the relative occurrence of each speed profile based on prevailing congestion levels. By selecting three speed profiles (P_I, P_{II} and P_{III}), it was intrinsically considered a discrete choice process. Discrete choice models are based on the theory of stochastic utility whereby a decision-maker makes a choice in order to maximize the utility function. This utility function, shown in **Eq. 2.1**, is constructed as a combination of known explanatory variables, the systematic part of utility, and a random part which is unknown (31).

$$U_{i,n} = V_{i,n} + \varepsilon_{i,n} \qquad \textbf{Eq. 2.1}$$

where $V_{i,n}$ is the systematic part of utility which is a linear function to predict the probability that decision maker n chooses alternative i (or, more generically, that a given observation n has an outcome i), and $\varepsilon_{i,n}$ represents the error between the systematic part of utility and the true utility assigned by user n to alternative i.

Assuming that the error term of the utility expression is logistically distributed, the multinomial logit model (MNL) is then obtained from **Eq. 2.2** (36):

$$P_n(i) = \text{Probability}\left(U_{i,n} > U_{j,n}\right) = \frac{e^{V_{i,n}}}{\sum_{j \in C_n}^{K} e^{V_{j,n}}} \qquad \textbf{Eq. 2.2}$$

where C_n is the choice set that the decision maker n faces.

For this application, the speed profile of a given vehicle can be expressed as a function of the sum of the entry and conflicting traffic flows ($Q_{total} = Q_{in} + Q_{conf}$), as an indirect measure of the congestion level (10). Since only differences are in the utility maker in influencing the choice, the outcome "P_I" (no stopping) was chosen as reference. The MNL probabilities for Profiles I, II and III are given by **Eq. 2.3**, **Eq. 2.4** and **Eq. 2.5**, respectively:

$$P(\text{Y} = "P_{\text{I}}") = \frac{1}{1 + e^{\beta_{2,0} + \beta_{2,1} Q_{total}} + e^{\beta_{3,0} + \beta_{3,1} Q_{total}}} \qquad \textbf{Eq. 2.3}$$

$$P(\text{Y} = "P_{\text{II}}") = \frac{e^{\beta_{2,0} + \beta_{2,1} Q_{total}}}{1 + e^{\beta_{2,0} + \beta_{2,1} Q_{total}} + e^{\beta_{3,0} + \beta_{3,1} Q_{total}}} \qquad \textbf{Eq. 2.4}$$

$$P(\text{Y} = "P_{\text{III}}") = \frac{e^{\beta_{3,0} + \beta_{3,1} Q_{total}}}{1 + e^{\beta_{2,0} + \beta_{2,1} Q_{total}} + e^{\beta_{3,0} + \beta_{3,1} Q_{total}}} \qquad \textbf{Eq. 2.5}$$

where $\beta_{2,0}$ and $\beta_{2,1}$ = intercept and coefficient for outcome "Profile II", and $\beta_{3,0}$ and $\beta_{3,1}$ = intercept and coefficient for outcome "Profile III".

2.3.5. Emission Estimation

VSP is the mechanical power used for the vehicle's motion and it is defined as the instantaneous power per unit mass of the vehicle. This instantaneous power generated by the engine is used to overcome rolling resistance and aerodynamic drag and to increase the kinetic and potential energy of the vehicle (26). This approach was selected since it can estimate instantaneous emissions based on second-by-second vehicle dynamics (speed, acceleration and grade) from instantaneous emissions data. VSP values are categorized in 14 engine regime modes, and an emission factor for each mode is used to estimate CO_2, CO, NO_X and HC emissions for LPV (25). Kolak et al. (37) and Coelho et al. (38) recognized that a VSP based emission model leads to a better estimation of vehicle emissions (37) and regional air quality concentrations (38) than an average speed-based emissions model. For a typical LPV, VSP is estimated as (12):

$$VSP = v.\left[1.1.a + 9.81.\sin\left(\arctan\left(grade\right)\right) + 0.132\right] + 0.000302.v^3 \qquad \textbf{Eq. 2.6}$$

where VSP is the Vehicle Specific Power (kW/ton), v is the vehicle instantaneous speed (m/s), a is the vehicle instantaneous acceleration or deceleration (m/s^2) and the *grade* is Terrain gradient (decimal fraction).

The average emission rates for pollutants CO_2, CO, NO_X and HC for each VSP mode for light passenger gasoline vehicles (LPGV), light passenger diesel vehicles (LPDV) and light commercial diesel vehicles (LCDV) are presented in **Table 2.2**. The LPGV values are the average tailpipe emissions from over forty LPV with engine size between 1.5 L and 2.5 L, gross weight from 1,070 kg to 2,086 kg, and mileage between 4,989 km and 368,186 km; the vehicle model years range from 1997 to 2012. The emissions were measured by a PEMS (27). The LPDV and LCDV emission rates can be found elsewhere (39).

The authors tried to fit the emission rates as far as possible to the characteristics of local fleet compositions, i.e. the engine capacity, average age of vehicles and fuel type. Such emission rates can be applied to a European car fleet (29, 40) since they include a wide range of engine displacement values.

The following distribution fleet composition was used for both roundabout layouts (41): 45% of LPGV, 34% of LPDV and 21% of LCDV. Analysis of the video footage showed a low number of heavy-duty vehicles (lower than 2%) in the selected case studies. Thus, they were not included in the emissions calculations.

Then the pollutant emissions per vehicle for the three speed profiles were aggregated to evaluate the overall impact of a change in the average path through the roundabout. **Eq. 2.7** provides the estimation of hourly emissions generated by vehicles entering a roundabout by using VSP methodology:

$$E_{TR} = Q_{in}\left(E_I \times P_I + E_{II} \times P_{II} + E_{III} \times P_{III}\right) \qquad \textbf{Eq. 2.7}$$

where E_{TR} are the hourly emissions at the turbo-roundabout (g); E_i is the emission per vehicle associated with each speed profile i = I, II and III (g); P_i is the proportion of vehicles that experienced each speed profile i = I, II and III; Q_{in} is the entry flow rate (vph).

Table 2.2 Mean Values for CO_2, CO, NOx and HC emission rates (g/s) for VSP modes for LPGV, LPDV and LCDV

Vehicle Type	Definition (kW/ton)	VSP Mode	Average modal emission rates			
			CO_2 (g/s)	CO (g/s)	NO_X (g/s)	HC (g/s)
Light Passenger Gasoline Vehicles (LPGV) (27)	**VSP[1] < -2**	**1**	1.04	0.00225	0.0003	0.00003
	-2 ≤ VSP < 0	**2**	1.31	0.00288	0.0004	0.00004
	0 ≤ VSP < 1	**3**	0.93	0.00179	0.0002	0.00003
	1 ≤ VSP < 4	**4**	2.17	0.00496	0.0008	0.00006
	4 ≤ VSP < 7	**5**	3.00	0.00743	0.0013	0.00008
	7 ≤ VSP < 10	**6**	3.77	0.00930	0.0018	0.00010
	10 ≤ VSP < 13	**7**	4.47	0.01223	0.0024	0.00011
	13 ≤ VSP < 16	**8**	5.05	0.01438	0.0029	0.00013
	16 ≤ VSP < 19	**9**	5.61	0.01954	0.0035	0.00015
	19 ≤ VSP < 23	**10**	6.01	0.02231	0.0040	0.00016
	23 ≤ VSP < 28	**11**	6.48	0.02914	0.0048	0.00017
	28 ≤ VSP < 33	**12**	6.96	0.03673	0.0055	0.00019
	33 ≤ VSP < 39	**13**	7.41	0.05438	0.0064	0.00020
	VSP ≥ 39	**14**	8.06	0.12828	0.0061	0.00023
Light Passenger Diesel Vehicles (LPDV) (39)	**VSP[1] < -2**	**1**	0.21	0.00003	0.0013	0.00014
	-2 ≤ VSP < 0	**2**	0.61	0.00007	0.0026	0.00011
	0 ≤ VSP < 1	**3**	0.73	0.00014	0.0034	0.00011
	1 ≤ VSP < 4	**4**	1.50	0.00025	0.0061	0.00017
	4 ≤ VSP < 7	**5**	2.34	0.00029	0.0094	0.00020
	7 ≤ VSP < 10	**6**	3.29	0.00069	0.0125	0.00023
	10 ≤ VSP < 13	**7**	4.20	0.00058	0.0155	0.00024
	13 ≤ VSP < 16	**8**	4.94	0.00064	0.0178	0.00023
	16 ≤ VSP < 19	**9**	5.57	0.00061	0.0213	0.00024
	19 ≤ VSP < 23	**10**	6.26	0.00101	0.0325	0.00028
	23 ≤ VSP < 28	**11**	7.40	0.00115	0.0558	0.00037
	28 ≤ VSP < 33	**12**	8.39	0.00096	0.0743	0.00042
	33 ≤ VSP < 39	**13**	9.41	0.00077	0.1042	0.00040
	VSP ≥ 39	**14**	10.48	0.00073	0.1459	0.00042
Light Commercial Diesel Vehicles (LCDV) (39)	**VSP[1] < -2**	**1**	0.29	0.00003	0.0015	0.00003
	-2 ≤ VSP < 0	**2**	0.84	0.00004	0.0039	0.00005
	0 ≤ VSP < 1	**3**	1.07	0.00004	0.0066	0.00004
	1 ≤ VSP < 4	**4**	2.55	0.00008	0.0094	0.00009
	4 ≤ VSP < 7	**5**	4.34	0.00016	0.0160	0.00013
	7 ≤ VSP < 10	**6**	6.14	0.00027	0.0254	0.00015
	10 ≤ VSP < 13	**7**	8.20	0.00044	0.0356	0.00025
	13 ≤ VSP < 16	**8**	9.90	0.00054	0.0433	0.00044
	16 ≤ VSP < 19	**9**	11.27	0.00060	0.0491	0.00068
	19 ≤ VSP < 23	**10**	12.34	0.00063	0.0518	0.00097
	23 ≤ VSP < 28	**11**	13.28	0.00071	0.0645	0.00082
	28 ≤ VSP < 33	**12**	15.77	0.00080	0.0736	0.00073
	33 ≤ VSP < 39	**13**	17.55	0.00091	0.0838	0.00083
	VSP ≥ 39	**14**	19.38	0.00103	0.0945	0.00093

[1] *As computed by* ***Eq. 2.6***

The emission values of CO_2, CO, NO_X and HC are estimated from the distribution of VSP time spent in modes obtained from the GPS runs. Therefore, E_i is given by the **Eq. 2.8**:

$$E_{ij} = \sum_{m=1}^{N_m} F_{mj} \qquad \textbf{Eq. 2.8}$$

where E_{ij} are the total emissions for source pollutant (g); m is the label for second of travel (s); i is the speed profile (I, II and III); j is the source pollutant; F_{mj} is the emission factor for pollutant j in label for second of travel m (g/s) and N_m is the number of seconds (s).

To estimate the pollutant emissions for each speed profile (E_i), second-by-second emission rates for the vehicles which experience that speed profile are obtained from **Eq. 2.6**. These speed profiles take into account the impact of the different traffic flow levels on the approach and circulating areas and thus on vehicle operating speed.

It should be emphasized that a fixed travel distance across the roundabout must be used to calculate the complete E_i second-by-second dynamics for a given speed profile. Thus, a roundabout influence area was defined as the sum of the deceleration distance that a vehicle travels from cruise speed as it approaches the roundabout, enters the circulating lane and acceleration distance as it leaves the roundabout up to the point it regains the cruise speed. For this analysis, an average roundabout influence area of 250 m was considered. Since the case study sites are on relatively flat grades (less than 2%) the effect of that parameter was negligible.

2.4. Results

This section presents and discusses the main results from discrete models and characteristic speed trajectories for turbo and multi-lane roundabouts. The pollutant emission impacts (CO_2, CO, NO_X and HC) of the two layouts are also compared.

2.4.1. Predictive Discrete Models

Two MNL models were obtained – one for multi-lane roundabouts and the other for turbo-roundabouts. The models were calibrated through maximum likelihood using SPSS software (**Table 2.3**). The sample comprised 3,162 observations in three two-lane roundabouts and 2,498 observations in three turbo-roundabouts. Each of these cases was recorded in a database with three fields: roundabout type (Multi-lane – ML or Turbo-roundabouts – TR), speed profile (P_I, P_{II} or P_{III}) and total traffic flow (15-min period).

Figure 2.5 illustrates the two calibrated MNL models. As expected, the probability of a driver being able to negotiate the roundabout without stopping (P_I) decreases as the total traffic flow increases. For values below 600 vph for the sum of entry and circulating flow, most vehicles enter the multi-lane roundabout without any stops. For the turbo-roundabout layout, this value fell by 200 vph (400 vph). About 50% of the vehicles that enter the multi-lane and turbo-roundabout with flow rates higher than 1,200 vph and 800 vph, respectively, face multiple stops.

Table 2.3 Calibrated coefficients for the MNL model

Multi-lane (ML) roundabouts							Turbo-roundabouts (TR)						
Speed profile	***x***	**B**		**Std. Error**	**Wald**	**Sig.**	**Speed profile**	***x***	**B**		**Std. Error**	**Wald**	**Sig.**
P_{II}	Intercept	-2.85	$\beta_{2,0}$	.17	276.3	.00	P_{II}	Intercept	-2.984	$\beta_{2,0}$	.16	340.7	.00
	Q_{total}	.003	$\beta_{2,1}$	.00	86.3	.00		Q_{total}	.002	$\beta_{2,1}$	.00	208.6	.00
P_{III}	Intercept	-7.55	$B_{3,0}$	.62	146.4	.00	P_{III}	Intercept	-8.619	$B_{3,0}$	.45	366.5	.00
	Q_{total}	.008	$B_{3,1}$	.00	62.0	.00		Q_{total}	.006	$B_{3,1}$	.00	295.3	.00

Legend: *for each of the model predictors, including the constant, B is the coefficient, SE is the standard error around that coefficient, and Wald is the Wald chi-square test* $\left(X_w^2 = B/SE\right)$ *that tests the null hypothesis that the constant equals 0. This hypothesis is rejected because the p-value (listed in the column "Sig.") is smaller than the critical p-value of 0.05.*

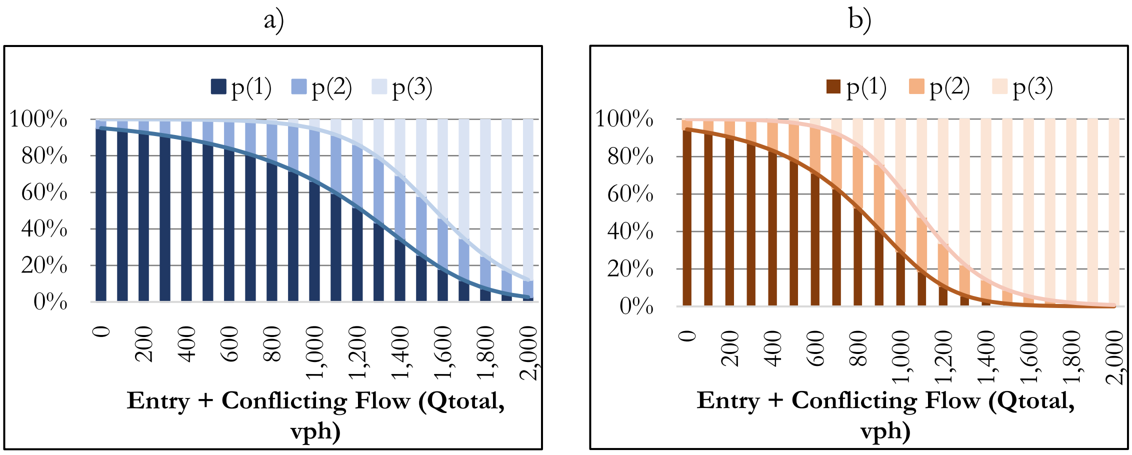


Figure 2.5 Predictive models for the relative occurrence of speed profiles I, II and III: a) multi-lane roundabouts; b) turbo-roundabouts.

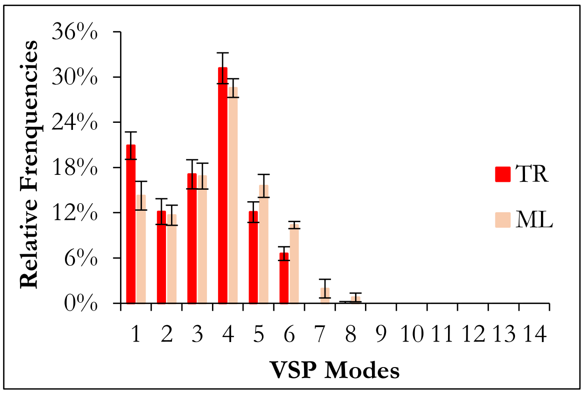
Therefore, the comparison of the two graphs shows that the probability for one or more stops (P_{II} and P_{III}) for the same total traffic is higher in the turbo-roundabouts. This happens because on the two-lane roundabouts the conflicting traffic is divided into two lanes, which increases the number of large gaps available for the vehicles waiting at the yield line (20). Concerning speed, there are no significant differences in the average approach speeds between roundabout layouts, as listed in **Table 2.1**. However, the differences in terms of conflicting traffic flows and roundabout geometry dictated some variation in the entry speeds at the yield line among the candidate case studies.

2.4.2. Vehicles trajectories at turbo-roundabouts and multi-lane roundabouts

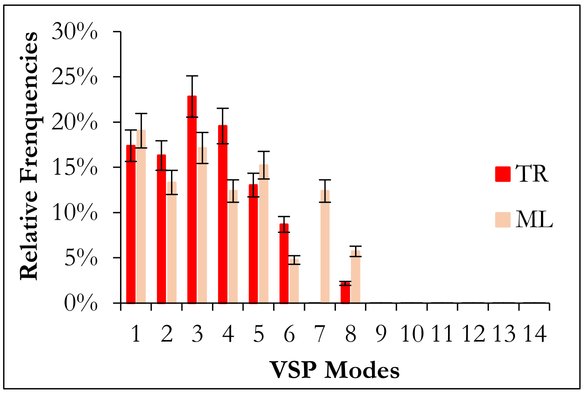
As mentioned before, the relative occurrence of the speed profiles was found to depend on the prevailing traffic demand at the roundabout ($Q_{total} = Q_{in} + Q_{conf}$). The video data from the turbo-roundabouts showed that low circulating speed values (see **Table 2.1** for those details) led to significant idle times and stop-and-go situations in the approach lane. Accordingly, the vehicle dynamics through the two layouts is rather different.

With this concern in mind, all the speed profile sets (I, II and III) for the turbo and multi-lane roundabouts were selected to assess the differences in emissions. The corresponding percentage of time in each VSP mode exhibited in **Figure 2.6** (*a-c*) is the average speed trajectories for a turbo-roundabout and a multi-lane roundabout (from the left entry lane) using multiple sets of GPS field data (considering all performed runs and all drivers). These speed trajectories are later used to estimate emissions from the turbo-roundabout and multi-lane roundabout using the predictive regression models developed for each case.

a)



b)



c)

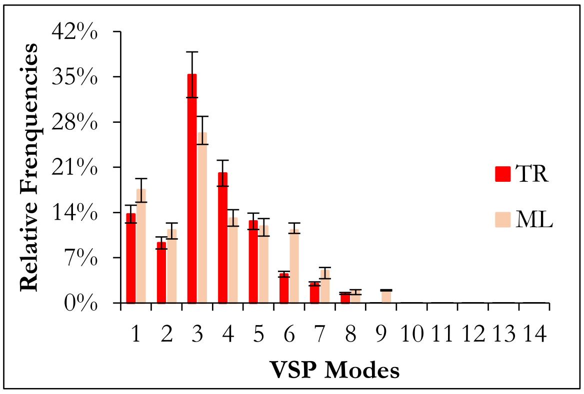


Figure 2.6 Total seconds spent in each VSP model (with 95% confidence intervals) for each speed profile: a) I, b) II, c) III.

Based on the raw distributions of VSP modes from the turbo-roundabout for speed profile I, vehicles spent most of the time in VSP modes 1, 2, 3, 4 and 5. This corresponds to decelerations as vehicles approach the turbo-roundabout (modes 1 and 2), enter the circulating lanes at low speeds or stop (mode 3) and accelerations as they exit the turbo-roundabout (modes 4 and 5). The percent of the time spent in VSP modes higher than 5 for the turbo-roundabout is slightly (≈3%) lower across the three speed profiles compared to multi-lane roundabout on speed profile I. This means, as expected, that vehicles at the turbo-roundabout experience lower speeds than those at the multi-lane layout (perhaps due to higher deflection level and low circulating speeds). Nevertheless, a vehicle travelling in turbo-roundabout faces more idling and low speed situations at the downstream and circulating areas than a vehicle travelling in a multi-lane roundabout, especially in speed profiles II and III. This is mostly because the lane dividers prevent drivers from using the full carriageway width to reduce curvature, which contributes to lower circulating speeds.

2.4.3. Emission Rates

This section employs the predictive discrete models and trajectories of the speed profiles I, II and III to calculate and compare the emissions produced by vehicles at a turbo-roundabout and a multi-lane roundabout. According to the different values of the entry and conflicting flows, the percentage of vehicles that experience any of the three speed profiles at a turbo-roundabout is identified from **Figure 2.5**. Next, the total emissions for each speed trajectory in each layout are calculated using **Eq. 2.6**, **Eq. 2.7** and **Eq. 2.8**.

Following the previous results, six traffic demand scenarios are established with the main goal of comparing the CO_2, CO, NO_X and HC emissions for the turbo-roundabout and multi-lane roundabout. The pollutant emission effects of both layouts were explored at two levels: *1*) sum of the entry and conflicting flows; and *2*) total saturation level. The following scenarios are:

- Scenario 1: $Q_{in} = Q_{conf} = 100$ vph ($Q_{total} = 200$ vph);
- Scenario 2: $Q_{in} = Q_{conf} = 200$ vph ($Q_{total} = 400$ vph);
- Scenario 3: $Q_{in} = Q_{conf} = 300$ vph ($Q_{total} = 600$ vph);
- Scenario 4: $Q_{in} = Q_{conf} = 400$ vph ($Q_{total} = 800$ vph);
- Scenario 5: $Q_{in} = Q_{conf} = 500$ vph ($Q_{total} = 1{,}000$ vph);
- Scenario 6: $Q_{in} = Q_{conf} = 600$ vph ($Q_{total} = 1{,}200$ vph).

These scenarios were based on the video footage of traffic flows on both roundabout layouts and the hypothesis of this study:

- Different flow rates affect emissions for multi-lane roundabouts and turbo-roundabouts;
- Vehicles in turbo-roundabouts face more stop-and-go situations than vehicles in multi-lane roundabouts, which might affect emissions;
- Highly congested and less congested traffic periods may have different effects on the emissions on both roundabout layouts.

The comparison of hourly emissions per vehicle (g/veh/h) for the turbo-roundabout and multi-lane roundabout for CO_2, CO, NO_X and HC is given in **Figure 2.7**. The results show that in both low and moderate congestion levels (scenarios 1-4) the pollutant emissions generated by vehicles at the turbo-roundabout are higher than those verified at the multi-lane roundabout (13%, 16%, 12% and 20% for CO_2, CO, NO_X and HC, respectively). For high flow rates (scenarios 5-6), turbo-roundabouts yield even more emissions than multi-lane roundabouts (19%, 23%, 19% and 29% for CO_2, CO, NO_X and HC, respectively). This is possible because of the longer stop-and-go cycles that vehicles experience at the turbo-roundabout since their speed profiles are mostly II (>22%) or III (>34%) in high flow rate scenarios.

On average, vehicles spent 23% more time crossing the turbo-roundabout than they spent on the multi-lane layout (assuming equal travel distances), which leads to higher emissions, as shown in **Figure 2.6**. This explains the similar yield trend in the CO_2, CO, NO_X and HC graphs. The main conclusion from **Figure 2.7** is that the time spent by vehicles as a result of the difference between cruise and circulating speeds has more impact on emissions at the turbo-roundabout than the deceleration-acceleration rates do (on average >7% over the multi-lane layout).

To sum up, the relative difference between emissions produced at the turbo and multi-lane roundabouts is not sensitive to the congestion level. These findings are in line with previous studies on turbo-roundabouts in which those layouts produced a higher amount of CO_2 and NO_X emissions than multi-lane roundabouts (29).

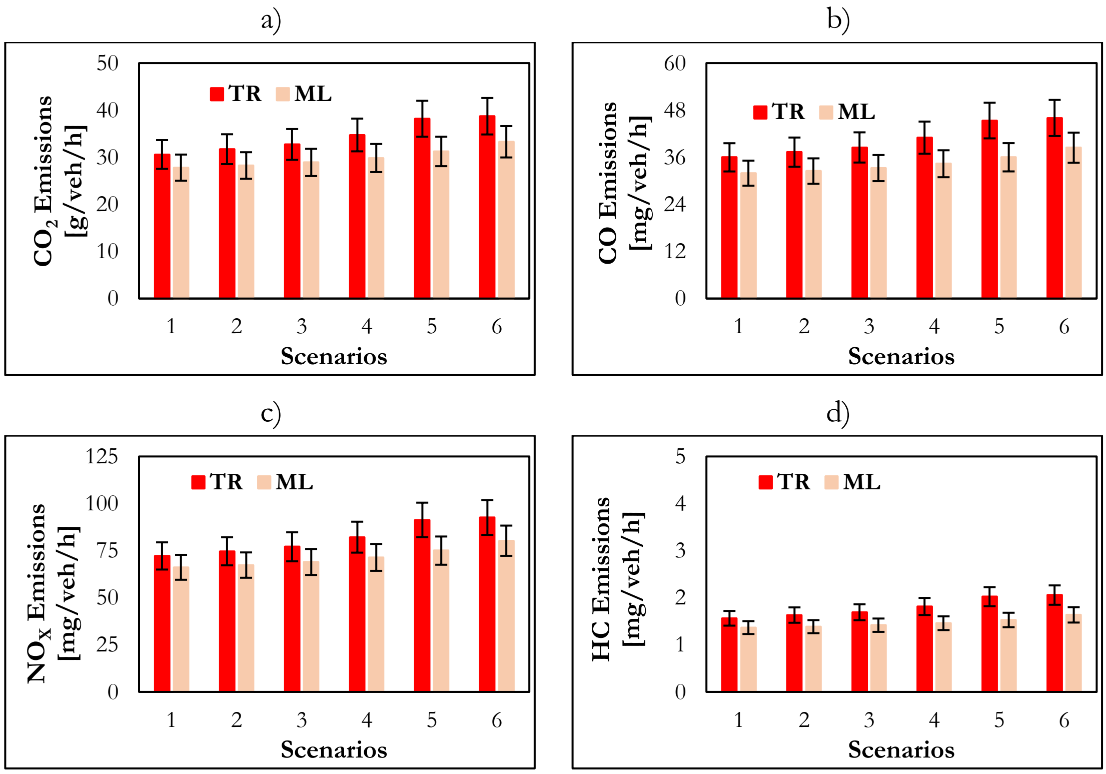


Figure 2.7 Hourly variation of the emissions per vehicle for different traffic scenarios (and 95% estimated confidence intervals): a) CO_2; b) CO; c) NO_X; and d) HC.

2.5. Conclusions

This paper addressed the impact of turbo-roundabouts on pollutant emissions and used a methodology and framework based on field measurements of vehicle activity and traffic flow data to estimate the emissions. The emissions for vehicles travelling in turbo-roundabout and multi-lane roundabouts were also compared. The methodology estimated overall emission via the following steps:

1) Discrete models were developed to establish a relationship between distinct speed profiles (no stop, stop once and several stops) that vehicles experience at turbo- and multi-lane roundabouts and traffic conditions (entry and conflicting flows).
2) A representative speed profile was chosen for each trajectory, assuming that each roundabout layout had similar approach speeds.
3) The VSP distribution was calculated for each representative trajectory (identified from Step 2).
4) The hourly pollutant emissions were calculated from discrete models that estimated the proportion of entry volume for each speed profile occurrence (Step 1), and multiplied them by the corresponding VSP for each trajectory.

The methodology and models used in this research can be applied by simply measuring turbo-roundabout and multi-lane layout volume characteristics and identifying a representative speed profile at the roundabouts. Step 1 (the hourly collection of entry and conflicting flows) enables the use of discrete models to estimate the percentage of vehicles that experience each profile (I, II and III). Step 2, in which the representative speed profiles are chosen, leads to the calculation of the VSP distribution of each trajectory (Step 3) for both layouts. Step 4, in which the hourly total emissions from the above steps are calculated (by multiplying the volume and percentage of each trajectory by the emission values per vehicle and summing up the results of the three trajectories).

This study highlights the importance of identifying some design features of intersections before implementing a multi-lane or turbo-roundabout to enhance both capacity and emission impacts. The major difference between the turbo and multi-lane layouts lies in the possibility of weaving and lane-change maneuvers in the circulating ring of the roundabout. The models developed in this work did not take into account those operational differences, but they were captured and reflected in the GPS runs.

The findings of this work showed that vehicles circulating in turbo-roundabouts, assuming a through movement, produced 15-22% more emissions (depending on the pollutant) than were produced at conventional multi-lane roundabouts. Although these results suggest that there is no advantage in implementing turbo-roundabouts from an environmental point of view, a transportation planner must consider the trade-off between emissions and safety. Turbo-roundabouts benefit safety by influencing control of driver behavior through the physical separation of the circulating lanes near the entry, on the circulatory path and at the exit zones. Removal of the crossovers that occur with conventional multi-lane roundabouts increases road safety significantly. Accordingly, these findings must be carefully analyzed before installing a turbo-roundabout. Work that can be developed in the future includes:

- Gathering more data on turbo-roundabouts, particularly, *1*) in those with different configurations (these three turbo-roundabouts have small inscribed circles and circulating widths); *2*) in those with higher traffic volumes; *3*) in those with greater variability in terms of approach speeds, geometries and traffic flows among turbo-roundabouts; and *4*) those where there is a raised divider that can affect vehicle maneuvers around the turbo-roundabout;
- Improving the developed predictive discrete models, which are based solely on entry and conflicting traffic, since they may have limited transferability for roundabouts with significant geometric differences or that operate under very distinct demand scenarios. They should be improved by linking the speed profile to the entry capacity and saturation rate. These performance measures can be effectively estimated using well-established models based on gap-acceptance theory. The resulting predictive models can then be applied to different geometries or directional splitting of the approaching traffic;
- Using a PEMS to collect field emissions on those sites or others with equivalent fleet composition would be useful and meaningful. This procedure would provide a validation of emission results and enhance the accuracy of the developed models.

2.6. Acknowledgments

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3. EMISSION HOTSPOTS IN ROUNDABOUT CORRIDORS

Chapter 2 showed that turbo-roundabouts generated higher emissions than multi-lane roundabouts, especially in high demand levels. Once this limitation identified, this chapter introduces several concepts to understand the distribution of emissions along corridors with conventional roundabouts. The chapter focuses on two main aspects. First, the identification of hotspot emission locations in the different segments along a corridor with interdependent roundabouts is conducted using empirical data. Second, the effect of corridor' design features (mainly spacing) on both acceleration profiles and emissions is examined.

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Abstract

This study describes a methodology to quantify and characterize the vehicular emissions of functionally interdependent roundabouts at a corridor level. Corridor segments include those upstream of each roundabout, the circulating area, downstream of the roundabout as well as midblock sub-segments between adjacent roundabouts. The main purpose of the study is to identify the locations along the corridors where emissions tend to be consistently high. These locations are termed "Emission Hotspots". The methodology is applied to four existing roundabouts corridors in San Diego (California) and Avon (Colorado) in the United States, and in Mealhada and Chaves (Portugal). An extensive sample of second-by-second speed traces is available for these four corridors with roundabouts.

The analysis shows that when roundabouts are fairly spaced and have similar geometric design features, no significant differences are observed between emissions of roundabouts located in the corridor. In such cases, the downstream sub-segments are the emission hotspots both in absolute terms (overall contribution on total emissions is higher than 34%) and per unit distance (22% higher than the average corridor value). When roundabouts are unequally spaced the highest emissions hotspots (more than 9% above the average corridor value) are found at the circulating area sub-segments. The results also demonstrate that the entry deflection angle has a slight impact on the spatial distribution of emissions especially in the case of closely spaced roundabouts.

Keywords: Roundabout corridors; Emissions; Vehicle Specific Power; Microscale analysis.

3.1. Introduction and Research Objectives

There has been a significant increase in the deployment of roundabouts in the past years in the United States (US). Currently there are approximately 2,360 roundabouts in place across the US (1). These types of intersections provide higher capacity levels compared to stop-controlled intersections (2) and are more effective in reducing unnecessary vehicle stops (3). Several studies in the US and Europe have demonstrated that roundabouts are safe for motor vehicles and pedestrians compared to other intersection forms (4). According to a report by the Federal Highway Administration (FHWA), there was a reduction of 44% and 82% in total and injury crashes, respectively, following the conversion of two-way intersections to roundabouts in the US (2).

Roundabout corridors have unique operational characteristics compared with roundabouts in isolation. Essentially, roundabouts do not allow the moving platoons of vehicles in order to maximize the performance efficiency since gap acceptance principles allow a more dispersed flows to move through the intersections (5). Still, all vehicles are expected to slow down to an appropriate speed for negotiating a roundabout and, as consequence, they experience a delay based on the geometry of the intersection and produce more emission, especially in acceleration-deceleration cycles.

However, there are some questions about their characteristics that have not been yet discussed. Firstly, if spacing between roundabouts is large enough so that speed patterns are identical to those observed at isolated roundabouts, this may not be considered a corridor. Secondly, the impact on queues may be particularly sensitive for very short spacing between roundabouts, and could suggest where the emission hot spots may be located. Third, the identification of the most congested roundabout in a series depends on traffic flows and directional splits. If all the queuing is located on the approach of the first roundabout, but the traffic flows completely through its downstream, the upstream roundabouts will not have negative impacts. On the other side, high congested mid-block section of a downstream roundabout can impact emissions on the upstream roundabouts.

With these concerns in mind, the motivation for this paper is to introduce a methodology to estimate emissions in the context of roundabout corridor. It is hypothesized that the design features that contribute to the spatial emissions distributions in the roundabout corridor and isolated roundabouts are different. More specifically, that the spacing between roundabouts has a greater impact on spatial emissions distributions in corridors compared to the entry deflection angle, as is the case at isolated roundabouts.

The novelty of this study is the analysis of pollutant emissions along a roundabout corridor, and the establishment of a relationship between them and corridor's design features, more precisely the spacing and the entry deflection angle of each roundabout. Based on the previous analysis of speed profiles along corridors, the authors are able to identify where the expected emission hot spots may be located. Finally, this research tests and verifies these predictions in four corridors with roundabouts with similar attributes, but with variation in the spacing between adjacent roundabouts. Thus, the main objectives of this research are:

- To analyze vehicular emissions for each pair of roundabouts throughout a corridor;
- To identify locations with the highest amount of emissions generated ("Emission Hotspots") through the corridor.

Section 3.2 presents a review of the technical literature. The methodology used in this research is explained in **Section 3.3**. Analysis results are presented and discussed in **Section 3.4**, followed by the main conclusions and the limitations of this research in **Section 3.5**.

3.2. Literature Review

Research in the field of transportation emissions has dealt with the environmental impacts of single-lane and multi-lane roundabouts installed at isolated intersections as well as in signalized corridors (6-9) and mixed traffic lights/roundabout corridors (10-12). Little research has been documented on traffic operations on a roundabout corridor level.

The few studies carried out in corridors with roundabouts did not consider the main design features that effect the spatial distributions of emissions. A study of a roundabout corridor with four roundabouts in Golden, Colorado evaluated crash rates, operating speeds, and travel times along the corridor (13). It was concluded that installing the roundabouts resulted in slower speeds between major intersections in the corridor, but there were also lower travel times compared to when the corridor was signalized. Isebrands et al. (14) reviewed corridors in Brown County, Wisconsin, and Edina, Minnesota. The authors found total crashes at one of the Wisconsin roundabouts were reduced by one per year and injury crashes were practically eliminated. Krogscheepers and Watters (15) assessed the average speeds, delays and travel times of six roundabouts along a rural corridor in South Africa and compared that with fixed-cycle traffic signals. The authors concluded that roundabouts offered operation advantages over traffic signals, but they recognized that roundabouts were inefficient under high demand scenarios. A study conducted in 58 US corridors developed a methodology for estimating travel speed and Level of Service (LOS) (16). Four different sub-models were developed to characterized traffic operations on those traffic facilities: Roundabout Influence Area Model, Geometric Delay Model, Free-Flow Speed Prediction Model and an Impeded Delay Model. However, above studies did not include the analysis of the emission impacts of roundabout corridors (15, 16).

In contrast, there is an extensive body of research focused on the environmental and energy performance of roundabouts installed at isolated intersections. Anya et al. (17) showed that the environmental benefits posed by a conversion of a signalized intersection to a two-lane roundabout in an urban corridor was only relevant, at the intersection-level, in the right turns movements from the minor street to the main street. Rakha et al. (18) demonstrated that both single and two-lane roundabouts yielded lower traffic delays and carbon monoxide (CO) emissions than one-way stop controlled in a three-way intersection. According to Mudgal et al. (19), acceleration events at the circulating areas and downstream sub-segments of roundabout contributed to more than 25% of emissions for a given speed profile. In (20), an empirically-based macroscopic methodology was introduced to compare emissions generated from roundabouts and signalized intersections. It was found that under low demand to capacity (d/c) ratios (<0.7) roundabouts generated lower emissions rates than traffic lights, while during oversaturation periods (d/c >1.0) roundabouts had a steady increase on emissions.

Other studies used models that integrated simulated vehicles dynamics data and microscopic modeling to estimate vehicle emissions at isolated roundabouts (21-23). The findings were inconclusive about the benefits from roundabouts concerning emissions reductions.

Based on field measurements from available research on roundabouts emissions (24, 25), there are three characteristics speed profiles for a vehicle approaching both a single or a multi-lane roundabout before entering the circulating lanes: *1*) vehicle does not stop (I); *2*) vehicle stops once (II) and *3*) vehicle stops multiple times (III). Coelho et al. (24) found that the relative occurrence of these profiles was dependent of the entry traffic and conflicting traffic flows. The same authors also suggested that higher deflection angles at the roundabout had a significant impact on emissions. Based on these findings, the same authors developed regression models for approaching vehicles at single-lane roundabouts in urban areas. Built on above research, Salamati et al. (25) developed regression models for each approaching lane (right and left) at multi-lane roundabouts. Although methodologies of above studies are generalized to estimate the footprints of emissions at roundabouts, its application cannot be extended to corridors. This is due to the fact that only traffic data related to the upstream and circulating areas sub-segments are considered. Even if the proposed methodologies were applied to each roundabout in the corridor, the contribution of mid-block sub-segment would not be included.

In summary, the literature review indicated that some studies were concerned about the environmental impacts at upstream, circulating areas and downstream sub-segments. Others studies focused on comparing isolated roundabouts and signalized intersections. None addressed the distribution of emissions across a corridor of roundabouts using empirical data.

The purpose of this research is to introduce a methodology to identify the emission hotspots along a roundabout corridor. The amount of pollutants is compared between different segments. Therefore, the focus of this study is not the actual amount, which would be affected by vehicle mix, but how the amount of emissions changes along a corridor as the speed and acceleration profiles changes. As for traffic volumes, this methodology focuses on microscopic emission evaluation along a roundabout corridor. The effect of traffic volume is mainly due the proportion of vehicles that experience type I, II or III speed profile at the roundabout and will help with hourly emission analysis. However, the authors clearly identified and defined the characteristics of the three speed profiles based on field observations during various traffic volumes. Therefore, the analysis and conclusions are independent of the traffic volume.

3.3. Methodology

This study is founded on field measurements of driver and vehicle characteristics. A summary of the methodological steps is depicted in **Figure 3.1**. To assist in the field data collection process, measurements were taken at four existing roundabout corridors located in San Diego California (La Jolla) and Avon Colorado (Avon) in the US, and Mealhada and Chaves (Portugal). For each location, the corridor was divided into multiple sub-segments as defined in the next section. Vehicle activity data such as second-by-second instantaneous speed, travel time, acceleration and road topographic conditions (grade) were collected using a Global Positioning System (GPS) data logger. Then, the Vehicle Specific Power (VSP) methodology was applied to estimate carbon dioxide (CO_2), CO, nitrogen oxides (NO_X) and hydrocarbons (HC) pollutant emissions for each sub-segment defined and through traffic movements. The selected case studies and vehicle activity data collection, as well as emissions calculations, are described in the following sections.

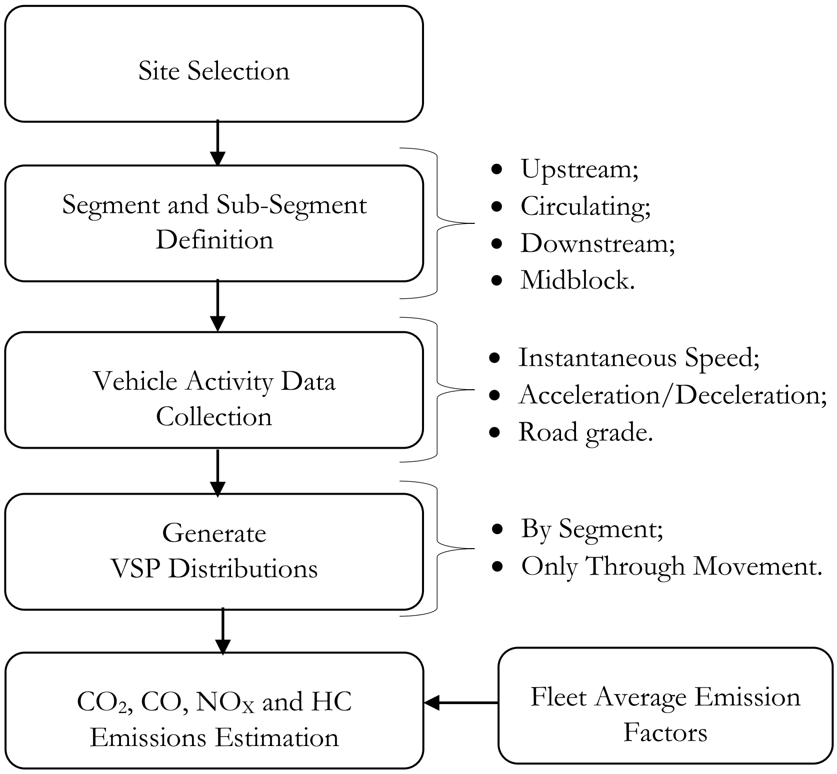


Figure 3.1 Summary of methodological steps.

3.3.1. Segments and Sub-segments Definitions

Before proceeding to the individual experimental results, this section offers key definitions of analysis segments. Each roundabout corridor is divided into multiple sub-segments in order to quantify the emissions impacts and identify the segments which consistently produce high emissions. This level of segmentation is motivated by changes in speed as drivers decelerate while approaching the roundabout, negotiate the circulating lanes and accelerate while exiting the roundabout. For the sake of consistency with the Highway Capacity Manual (HCM) the corresponding Urban Street segment is defined from the downstream yield lane from one roundabout to the upstream yield lane of the adjacent roundabout (in the direction of travel) (3).

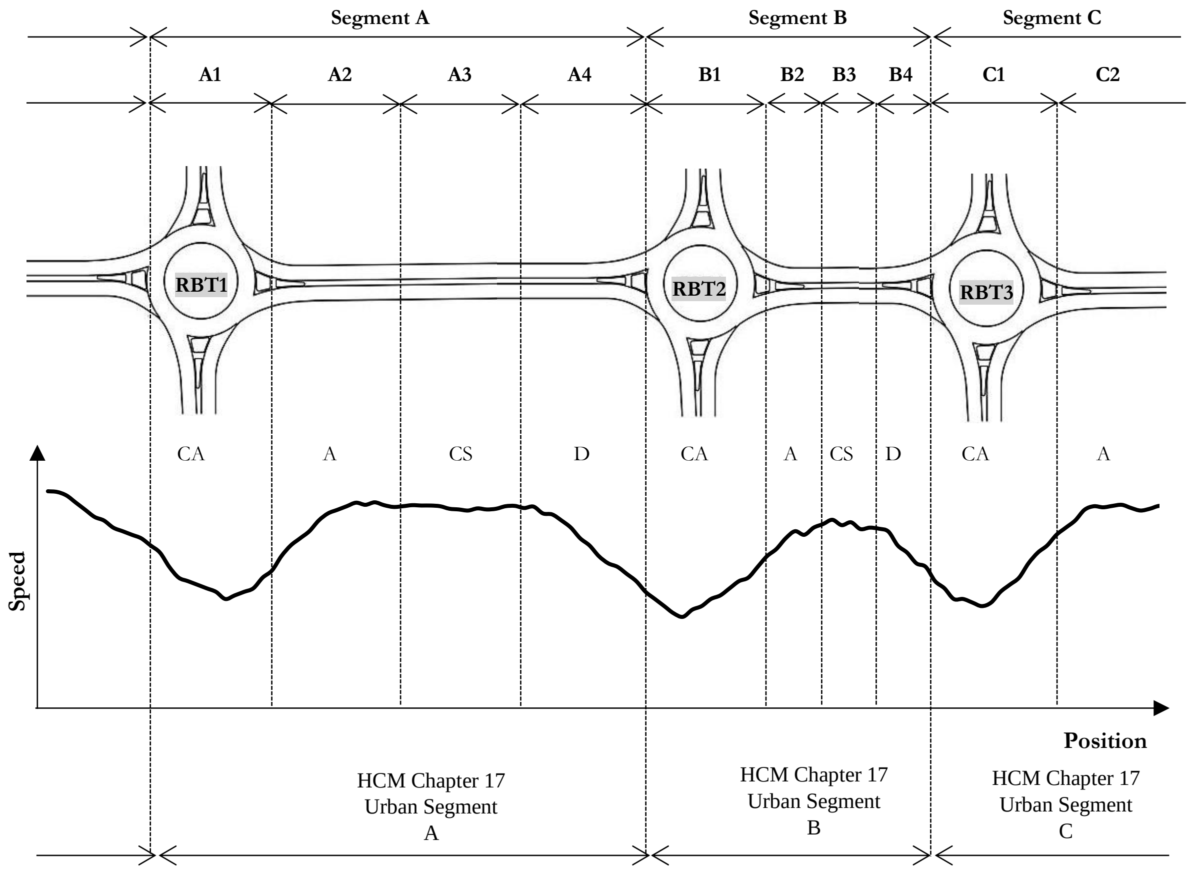
The proposed segmentation is illustrated in **Figure 3.2** for a specific through movement. The exhibit shows two pairs of roundabouts RBT1/RBT2 and RBT2/RTB3, separated by Segments A and B, respectively. Based on vehicle activity data and patterns in speed profiles, the research team identified four different sub-segments in which speed and acceleration patterns are different. In the case of Segment A (remaining segments have similar descriptions):

- Sub-segment A1: Vehicle decelerates to negotiate traffic in the circulating area of RBT1 and then accelerates while exiting the roundabout circle (deceleration/acceleration pattern);
- Sub-segment A2: Vehicle accelerates after exiting the roundabout back to cruise speed (acceleration only);

- Sub-segment A3: Vehicle operates at cruise speed without significant acceleration or deceleration rates (constant speed);
- Sub-segment A4: Vehicle begins to decelerate while approaching the downstream roundabout (deceleration only).

Sub-segments A1, B1 and C1 correspond to the downstream influence area of each roundabout, while A4 and B4 correspond to the upstream influence area of each roundabout. Midblock sub-segments are associated with sub-segments A3 and B3.

A key important concept is the definition of the length of the roundabout influence. Conceptually, a Roundabout Influence Area (RIA) is defined to include the roundabout circulating area and any upstream and downstream distance needed for deceleration/acceleration from/to free-flow speed (unimpeded speed) through the corridor (16). It is important to note that in the case of closely spaced roundabouts, the RIA from an upstream roundabout might overlap with an RIA from a downstream roundabout and therefore the vehicle would not be able to reach cruise speed (e.g. sub-segment B3). Therefore, this may not always be the case, and such sub-segment might exist in some corridors with roundabout and such design characteristic will have an impact on vehicle speed profile and thus emissions.



Legend: CA: Circulating area; A: Acceleration; CS: Cruise Speed; D: Deceleration.

Figure 3.2 Segments and sub-segments definition for a roundabout corridor and illustrative speed profile.

3.3.2. Sites Selection

Figure 3.3 shows an aerial map of the data collection sites investigated in this study as well as segments and sub-segments identification for the through movements, based on the definitions in **Figure 3.2**.

The team selected four corridors of functionally interdependent roundabouts because they included the following range of attributes: *1*) the number of roundabouts per corridor was similar (4/5); *2*) corridor length was similar; *3*) similar spacing between adjacent roundabouts (ranged from 120 m/400 ft. to 350 m/1150 ft.), but very different in the variation in spacing; *4*) low posted speed limits (<50 km/h), and *5*) a relatively constant traffic flow along the main arterials.

The first and second study locations are respectively in San Diego, California (**Figure 3.3**-a) and Mealhada, Portugal (**Figure 3.3**-b). The free-flow speed is fairly constant along these corridors, and the spacing is approximately equal between adjacent roundabouts (coefficient of variability of average spacing is <0.12).

The remaining corridors are located in Avon, Colorado (**Figure 3.3**-c) and in Chaves, Portugal (**Figure 3.3**-d). In these sites, the spacing between the roundabouts is not uniform (coefficient of variability of average spacing is >0.27).

All corridors are placed in urban environments. It should be noted that both Avon and Chaves sites have two pairs of adjacent roundabouts (RBT3 and RBT4) located in close proximity to each other and therefore make the case for overlapping RIAs for these corridors.

Table 3.1 lists each site where data was collected, including location, inscribed circle diameters, entry deflection angle, distance between adjacent roundabouts (measure from the upstream yield lane), length of the corridor and some descriptive statistics. Traffic data information is also provided.

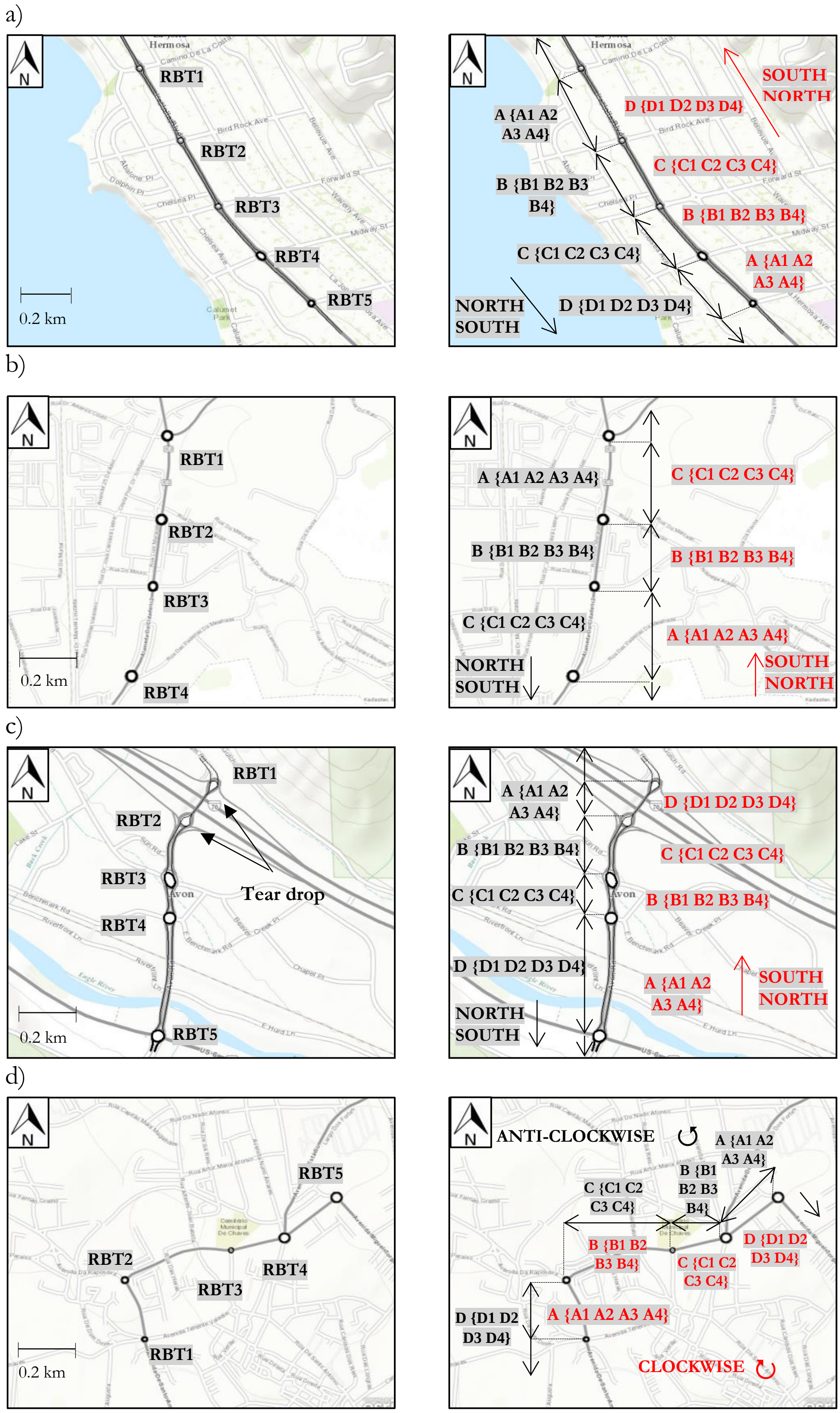


Figure 3.3 Aerial Map of the Data Collection Roundabout corridor and segments identification: a) La Jolla; b) Mealhada; c) Avon; d) Chaves. Source: http://www.arcgis.com

Table 3.1 Key characteristics of selected corridors

Site	ID	Number of circulating lanes	Inscribed Diameter [m]	Central Island [m]	Legs	Entry deflection angle (north-south/ south-north)[a]	Distance from upstream Roundabout [m]	Length of the corridor [m]	Spacing [m]		Peak Hour Traffic Volumes [vph]	
									Average	Coefficient of Variation	Arterial	Side Streets
La Jolla	RBT1	One	25	16	4	30º/31º	–	970	218.8	0.10	1,000 – 1,500	100 – 200
	RBT2	One	24	15	4	29º/30º	248					
	RBT3	One	25	14	4	34º/29º	227					
	RBT4[b]	One	22/25	15/19	4	22º/31º	192					
	RBT5	One	24	15	3	32º/31º	208					
Mealhada	RBT1	One	36	23	4	37º/36º	–	1,080	302.7 **(38%)**[d]	0.11 **(9%)**[e]	1,000 – 1,400	80 – 250
	RBT2	One	40	24	3	29º/31º	318					
	RBT3	One	35	23	4	37º/41º	255					
	RBT4	One	38	29	3	40º/43º	335					
Avon	RBT1[c]	Two	42	24	3	20º/-	–	805	197.0 **(-10%)**[d]	0.46 **(376%)**[e]	1,300 – 1,800	300 – 1,000
	RBT2[c]	Two	48	28	3	-/28º	144					
	RBT3	Two	46	23	4	23º/30º	170					
	RBT4	Two	45	28	4	34º/42º	124					
	RBT5	Two	44	26	4	39º/38º	350					
Chaves	RBT1	Two	22	10	5	51º/40º	–	1,175	238.0 **(9%)**[d]	0.28 **(159%)**[e]	800 – 1,200	200 – 500
	RBT2	Two	23	11	3	36º/15º	245					
	RBT3	Two	23	10	3	39º/16º	344					
	RBT4	Two	35	20	5	44º/46º	162					
	RBT5	Two	40	26	4	30º/32º	226					

Notes: *Coefficient of variation – Standard deviation/mean; peak hour was identified to occur between 5:00 p.m. and 6.00 p.m.*

a For Chaves corridor, the first and second entry deflection angles are in clockwise and anti-clockwise directions, respectively.

b Oval roundabout which has two values for Inscribed Diameter and Central Island.

c Roundabouts 1 and 2 are tear drop interchange roundabouts.

d Bold values are computed using the following equation: 100 × (average spacing of the site – average spacing of the LaJolla site)/average spacing of the LaJolla site.

e Bold values are computed using the following equation: 100 × (coefficient of variation of the site – coefficient of variation of the LaJolla site)/coefficient of variation.

3.3.3. Vehicle Activity Data and Emission Modeling

For vehicle activity characterization, second-by-second vehicle dynamics data were used. A Light Duty Gasoline Vehicle (1.5<LDGV<2.5l) made several runs through corridors. These runs were performed during morning, evening and off-peak periods (from 7 a.m. to 7 p.m.). The research team scouted and collected data at the four selected corridors in the fall of 2011, 2012 and 2015.

A QSTARZ GPS Travel Recorder (26) was employed to obtain some of the parameters related to the vehicle activity data (such as instantaneous speed) and the selected sites characteristics (road grade, latitude and longitude). To include a wide range of driving habits, different drivers (with vary levels of experience) performed an identical number of trips (approximately 10 each one) on each through movement.

Second-by-second vehicle activity can be characterized by "Vehicle Specific Power" (VSP) and modal emission factors developed from instantaneous emissions data. This microscopic emissions model was chosen since it allows estimating instantaneous emissions based on a second-by-second vehicle's dynamics (speed, acceleration and slope).

The VSP values are categorized in 14 modes of engine regime, and an emission factor for each mode is used to estimate CO_2, CO, NO_X and HC emissions. **Figure 3.4** depicts the VSP modes distribution for a generic Light Duty Vehicle (LDV) according with instantaneous speed and acceleration for a road grade of 0%.

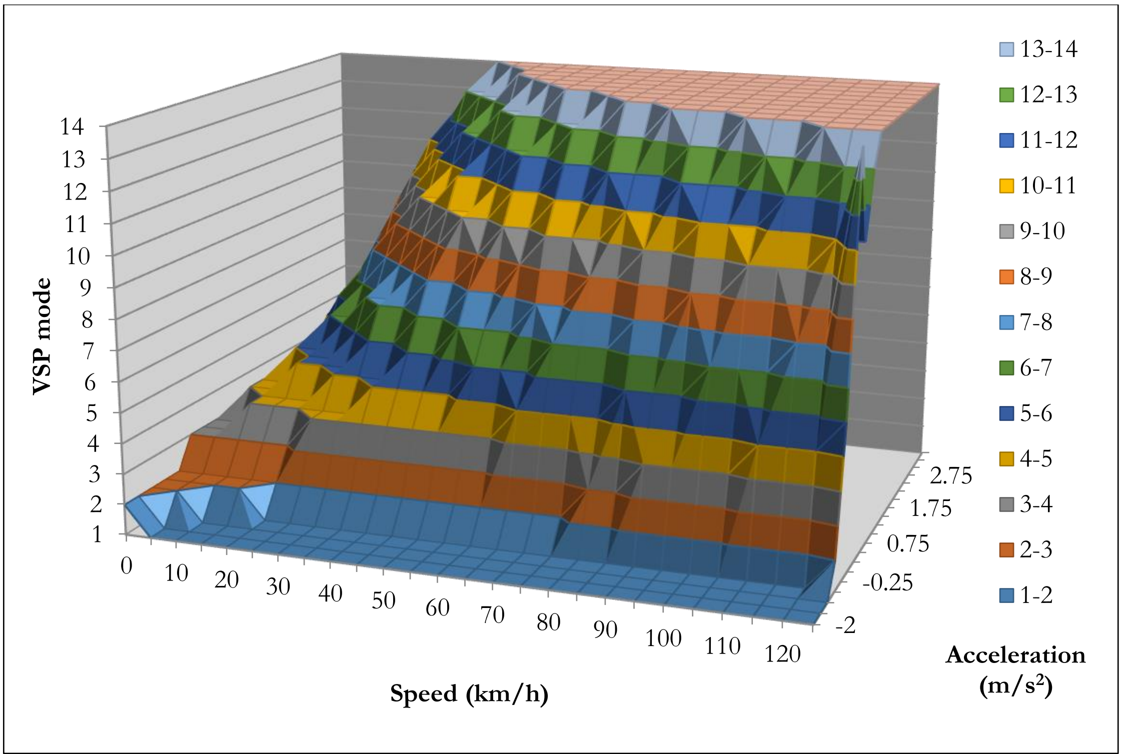


Figure 3.4 VSP modes distribution of a generic light duty vehicle for a road grade of 0%.

VSP is recognized to be very useful in estimating micro-scale emissions for both gasoline (27, 28) and diesel vehicles (29). Some previous studies have documented the effectiveness of the VSP approach in analyzing emission impacts of roundabouts (17, 19, 24, 25, 30). **Eq. 3.1** applies VSP to specific case of a typical Light Duty Gasoline Vehicle (LDGV) (28):

$$VSP = v.\left[1.1.a + 9.81.\sin\left(\arctan\left(grade\right)\right) + 0.132\right] + 0.000302.v^3 \qquad \textbf{Eq. 3.1}$$

where VSP is the Vehicle Specific Power (kW/ton), v is the vehicle instantaneous speed (m/s), a is the vehicle instantaneous acceleration or deceleration (m/s^2) and the $grade$ is Terrain gradient (decimal fraction).

Table 3.2 shows the average emission rates for pollutants CO_2, CO, NO_X and HC by VSP mode for a LDGV with an odometer reading range from 4,989 km (3,100 miles) and 368,186 km (228,780 miles) and engine displacement between 1.5l to 2.5l. These values are the average of tailpipe emissions measures gathered from over 40 LDGV using a Portable Emissions Measurement System (PEMS) at North Carolina State University (NCSU) (17).

Table 3.2 Fleet Average[a] Values of Emissions Rates by VSP Mode

VSP Mode	VSP Range [kW/ton]	Pollutants			
		CO_2 [g/s]	CO [mg/s]	NOx [mg/s]	HC [mg/s]
1	**VSP<-2**	1.04	2.25	0.31	0.29
2	**-2≤VSP<0**	1.31	2.88	0.41	0.35
3	**0≤VSP<1**	0.93	1.79	0.19	0.26
4	**1≤VSP<4**	2.17	4.96	0.82	0.56
5	**4≤VSP<7**	3.00	7.43	1.28	0.78
6	**7≤VSP<10**	3.77	9.30	1.81	0.96
7	**10≤VSP<13**	4.47	12.23	2.40	1.13
8	**13≤VSP<16**	5.05	14.38	2.90	1.32
9	**16≤VSP<19**	5.61	19.54	3.54	1.48
10	**19≤VSP<23**	6.01	22.31	3.98	1.59
11	**23≤VSP<28**	6.48	29.14	4.79	1.73
12	**28≤VSP<33**	6.96	36.73	5.49	1.86
13	**33≤VSP<39**	7.41	54.38	6.41	2.03
14	**39≤VSP**	8.06	128.28	6.06	2.28

a Based on measurements from 42 light duty gasoline vehicles (17)

Since this study focused on emissions along individual sub-segments of roundabout corridors, emissions values of CO_2, CO, NO_X and HC pollutants are estimated from the distribution of percentage of time spent in each mode obtained from the GPS runs, according to the **Eq. 3.2**:

$$E_{jK} = \sum_{i=1}^{N_K} F_{ijK} \qquad \textbf{Eq. 3.2}$$

where E_{jK} are the total emissions for sub-segment K and source pollutant j, i is the label for second of travel, j is the source pollutant, K is the sub-segment label; F_{ijK} corresponds to the emission factor for pollutant j in second of travel I on sub segment K (g/s) and N_K is the travel time on sub-segment K (s).

Then, the total emissions on a roundabout corridor is defined as the sum of emissions on each sub-segment across all roundabouts segments taking into account the number of roundabouts on the corridor, as expressed by **Eq. 3.3**:

$$E_j = \sum_{K} E_{j_K} \qquad \textbf{Eq. 3.3}$$

where E_j is the overall corridor emissions for pollutant j (g) and K is the analyzed sub-segment.

To maintain consistency among runs, a fixed travel distance across the corridors and for sub-segments must be used. Since the raw trajectories provide speed on a second-by-second basis, interpolation is needed to ensure that the emissions are correctly attributed to each sub-segment.

For the purpose of analysis, and supported by experimental measurements performed on the selected corridors, the downstream, midblock and upstream sub-segments are assumed to be equal in length. The segmentation is consistent with the HCM urban street procedure (3) and this methodology was chosen for the sake of simplicity and the fact that can be consistently applied to other roundabout corridors.

It should be also emphasized that this assumption is reasonable for the selected corridors because the spacing between roundabouts is not very long (<350 m). In the case of fairest adjacent roundabouts, mid-block segments are much longer that the downstream and upstream sub-segments, and therefore that assumption is not valid. However, such corridors are beyond the scope of this paper.

3.4. Results

In this section, the main results from the characteristics speed trajectories are presented and discussed (**Section 3.4.1**). Following that, the emissions per vehicle for each sub-segment on the selected corridors (**Section 3.4.2**) and per unit distance (**Section 3.4.3**) are estimated. Next, the spatial distribution of acceleration and CO_2 emissions of both corridors are analyzed (**Section 3.4.4**). This section concludes with the examination of the relationship between emissions and corridor design features (**Section 3.4.5**).

3.4.1. Characteristic Speed Trajectories

70 GPS travel runs in the two directions of travel were examined for this research (total of 560 speed profiles). This number of GPS data samples provides a suitable representation of the local traffic conditions.

Figure 3.5 (a-h) exhibits the speed trajectories through the corridor and the correspondent percent time spent in each VSP mode. These speed trajectories are later used to estimate emissions for each pre-defined sub-segments of the corridor.

The speed profiles across La Jolla (**Figure 3.5**a-b) and Mealhada (**Figure 3.5**c-d) corridors are highly symmetrical. Vehicles accelerate to cruise speed upon exiting each roundabout as they approach each mid-block sub-segment. However, vehicle speeds in mid-block sub-segments are lower than free-flow speeds. Higher acceleration rates are recorded in downstream segments of each roundabout of the corridor on both directions. Based on the raw distributions of VSP modes, vehicles spend most of the time in VSP modes 2, 3 and 4 which corresponds to; *a*) deceleration as vehicles approach the roundabout (Mode 2), *b*) enter the circulating lanes at low speeds or stop before negotiate the roundabout (Mode 3), and *c*) acceleration as they exit the roundabout (Mode 4).

The results from the Avon (**Figure 3.5**e-f) and Chaves (**Figure 3.5**g-h) corridors show that the highest average speeds occur at the RBT4/RBT5 and RBT2/RBT3, respectively. This is possibly due to the moderate spacing between those pairs of roundabouts, which is approximately 350 m (1,150 ft.) on both sites. The distance enables vehicles to attain and maintain free-flow speeds. Accordingly, the percentage of time spent in VSP mode 4 and 5 is higher than the speed for corresponding segments in La Jolla corridor. On the remaining roundabouts, the speed values are not as high. This is particularly true in the mid-block area between closely-spaced roundabouts RBT3 and RBT4 for which their distance is lower than 125 m (410 ft.) and 165 m (541 ft.) for Avon and Chaves corridors, respectively. It is also important to note that the roundabout influence area (RIA) for RBT3 and RBT4 overlap each other, especially in the Chaves corridor. Therefore, the maximum speed at mid-block segments are substantially below of what is observed at the remaining mid-block sub-segments. The percent of time spent in VSP Mode 3 (≈37%) confirms these findings.

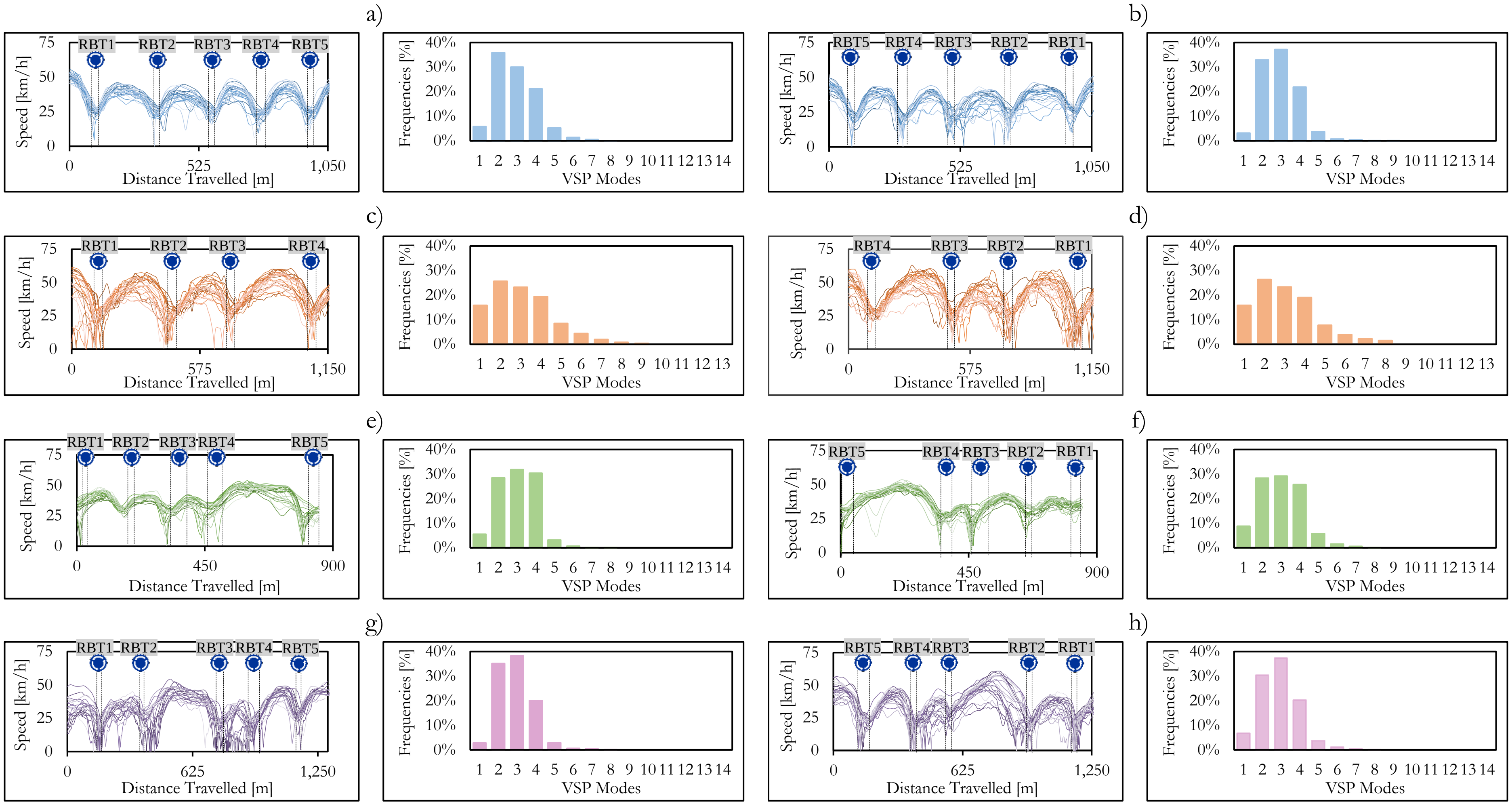


Figure 3.5 Speed trajectories by distance traveled for each through movement and corresponding raw distributions of VSP modes by corridor: (a) La Jolla (north–south); (b) La Jolla (south–north); (c) Mealhada (north–south); (b) Mealhada (south–north); (e) Avon (north–south); (f) Avon (south–north); (g) Chaves (clockwise); and (h) Chaves (anti-clockwise).

3.4.2. Segments and Sub Segments Emissions

This section uses the findings obtained previously to estimate the emissions of each specified segment (A, B, C and D) and their respective sub-segments for the four corridors. The second-by-second emissions are obtained using **Eq. 3.1** while total emissions for each sub-segment and overall segment are determined from **Eq. 3.2** and **Eq. 3.3**, respectively. Sub-segments E1 and E2 (D1 and D2 in the case of Mealhada corridor) are excluded from the analysis.

Figure 3.6a-b illustrates that the highest amount of CO_2 and CO emissions per vehicle, which is about 35% of the total emissions in La Jolla corridor, is produced in sub-segments A2, B2, C2 and D2 (downstream). These sub-segments correspond to about 29% of the travel distance and travel time across the corridor. This is mainly due to higher acceleration rates that vehicles experience as they exit each roundabout (**Figure 3.5**a-b), which are especially relevant for CO emissions. Albeit high, vehicles speeds in mid-block sub-segments (A3, B3, C3 and D3) did not result in a substantial impact on emissions (overall contribution on total CO_2 and CO emissions is about 23% for both through movements). This is due to the smooth speed profiles at those locations.

The findings from the Mealhada corridor (**Figure 3.6**c-d) show an identical trend. Specifically, downstream sub-segments (A2, B2 and C2) generated the highest amount of CO_2 and CO (35% on both gases) in 27% of travel distance and travel time. Because of the large distance between some of the roundabouts, vehicles often reach cruise speed in the midblock section (A3, B3 and C3) as they leave one roundabout RIA and travel toward the adjacent roundabout. Accordingly, sub-segments A3, B3 and C3 (upstream) contribute to more than 26% of total CO_2 and CO emissions in the corridor (they comprise about 29% and 22% of travel distance and travel time, respectively).

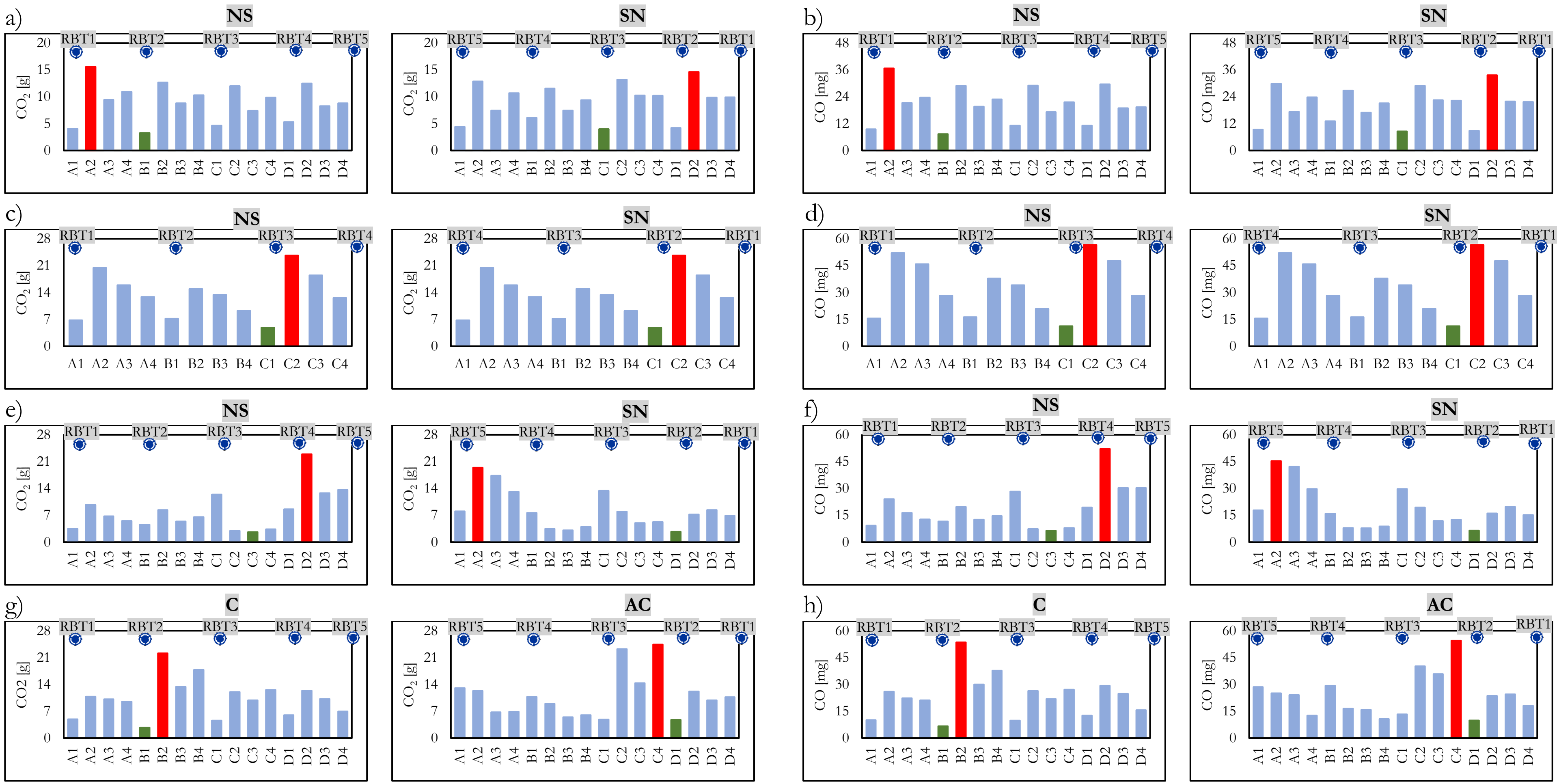
Regarding the assessment of each pair of roundabouts across La Jolla and Mealhada corridors, that is, segments A, B, C and D (in the case of La Jolla), the findings point to small differences in emissions both in CO_2 and CO pollutants. In such cases, emissions contributions from each segment range from 24% (segment C) to 28% (segment A) for La Jolla, and between 29% (segment B) and 35% (segment A) in the Mealhada site. Several explanations support these results. First, the distance between consecutive roundabouts is similar along the corridor. Second, specific geometric design aspects of each roundabout, such as inscribed diameter or the number of circulating lanes, do not vary. See **Table 3.1** for those details.

Sub-segments A2, B2, C2 and D2 also have a major impact on CO_2 emissions across the Avon corridor. According to **Figure 3.6**e-f, vehicles emit about 31% and 32% of CO_2 and CO, respectively, in 25% and 23% of travel distance and travel time respectively on both directions. Similarly, sub-segments A1, B1, C1 and D1 have a significant effect on emissions along that corridor, especially in CO. This is mostly because of the high inscribed diameter at those roundabouts.

Considering the Chaves site (**Figure 3.6**g-h), vehicles driving through downstream sub-segments also generate the highest amount of CO_2 and CO emissions (≈32% in both gases) of the corridor.

In summary, the results show that due to different lengths of each segment in the Avon and Chaves corridors there is a difference in CO_2 and CO emissions for each pair of roundabouts.

In the first corridor, and as suspected, the highest amount of overall emissions is produced between RBT4 and RBT5 roundabouts (Segments D and A on north-south and south-north movements, respectively). That segment represents 42% of the travel distance and, consistently, 43% of the total emissions. In contrast, segments C (north-south) and B (south-north) represent only 16% of the total emissions (they comprise about 14% of travel distance). In the second corridor, the impact of shortest length segments (C-clockwise and B-anti-clockwise) is high. They contribute to 22% and 23% of the total CO_2 and CO emissions, respectively in 17% of travel distance. Analysis of NO_x and HC emissions per vehicle resulted in same findings as the CO_2 and CO emissions.



Note: Red bar – High emission sub-segment; Green bar – Low emissions sub-segment; NS: north-south; SN: south-north; C: clockwise; AC: anti-clockwise.

Figure 3.6 Emissions (g) per vehicle for each sub-segment across the roundabout corridor: a) CO_2 La Jolla; b) CO La Jolla; c) CO_2 Mealhada; d) CO Mealhada; e) CO_2 Avon; f) CO Avon; g) CO_2 Chaves; h) CO Chaves.

3.4.3. Emissions rates per unit distance

Figure 3.7a-h illustrates the CO_2 and CO emissions per unit distance by sub-segment and regarding the overall corridor. The sub-segments associated to the downstream (A2, B2, C2 and D2) produce the highest amount of emissions per kilometer travelled across La Jolla corridor. In particular, these sub-segments generate higher CO_2 emissions per unit distance, 27% higher (210 g/km – north-south) and 18% higher (198 g/km – south-north) to the average values of the corridor; and an amount of CO emissions 48% and 21% higher than the average value of the corridor on north-south and south-north directions, respectively. Moreover, some circulating sub-segments reach emissions per unit distance higher than averages values which are recorded in both movements, especially in CO. On average, carbon monoxide emissions per unit distance at the circulating sub-segments (A1, B1, C1 and D1) are higher by 15% (385 mg/km) and 3% (387 mg/km) over the average value (376 mg/km) of the corridor.

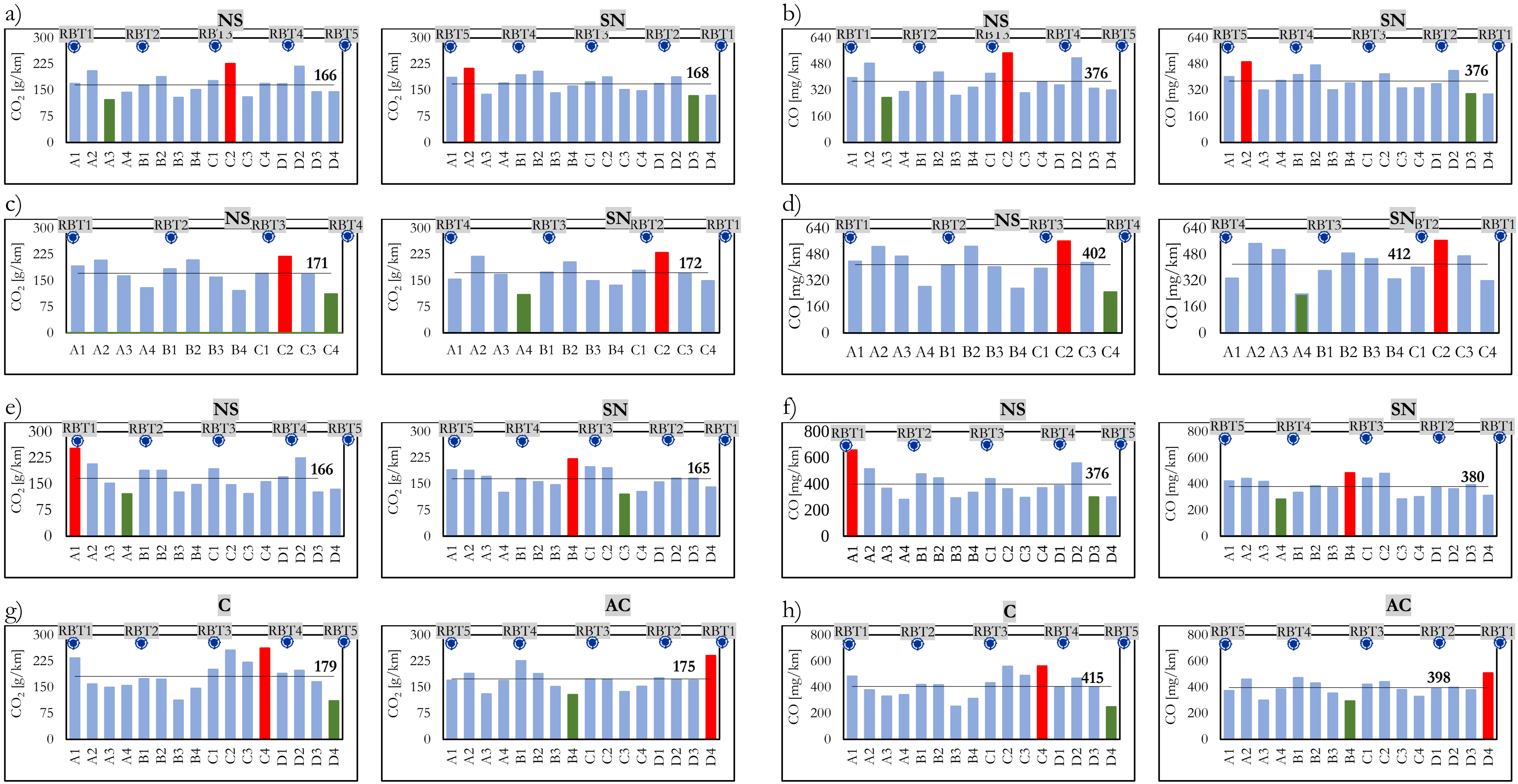
The downstream sub-segments (A2, B2 and C2) are also the emission hotspots in both directions of the Mealhada corridor: 25% more CO_2 and nearly 30% more CO emissions than the average values. Nevertheless, the impact of mid-block sub-segments is relevant on CO emissions (>10%). This happens because vehicles experience several stop-and-go situations at the upstream sub-segments of RBT4 and RBT1 that leads to higher deceleration rates in the prior sub-segment (mid-block).

It should be mentioned that when vehicles are crossing each pair of roundabouts, both global (CO_2) and local pollutant (CO) emissions per unit distance follow a similar trend in these corridors. For example, for Segment A, it is observed that emissions per unit distance increase from sub-segment A1 to A2. After that, they decrease on sub-segment A3 and again, increase on sub-segment A4 (**Figure 3.7**a-d). A2 and A3 are related to the highest and lowest emissions per unit distance sub-segments, respectively, within Segment A.

The analysis results show that the emissions hotspots in the Avon corridor are generated in the circulating areas of the roundabouts (A1, B1, C1 and D1). The impact of those sub-segments is more significant in CO emissions (27% higher than the average corridor values) when compared to CO_2 emissions (15% higher than the average corridor value). Concurrently, vehicles at any downstream sub-segments generate approximately 13% and 25% higher than the average corridor amount of CO_2 and CO emissions per unit distance, respectively. The findings for closely spaced roundabouts (RBT3 and RBT4), as illustrated in **Figure 3.7**e-f, prove that CO_2 emissions per kilometer travelled at the downstream (C2 and B2 in the north-south and south-north movements, respectively) are much smaller than those which are observed in equivalent sub-segments. Since vehicles have not enough distance to attain free-flow speeds, low acceleration rates are observed at the downstream sub-segment.

The circulating areas in the Chaves study location are associated to the highest emission rates per unit distance (9% higher than the average corridor value for CO_2 and CO). Interestingly, emissions per unit at the sub-segments between closely-spaced roundabouts (RBT3/RB4) are significantly different in both through movements. This point is explained by high stop-and-go situations in approach area of RBT4 (caused by high number of legs and resulting circulating traffic), which is not observed in RBT3 (it has three legs). Therefore, the highest emissions rates are yielded in segment C in the clockwise movement.

In summary, the comparison of pairs of corridors results in distinct emission hotspots. Vehicles at the downstream sub-segments produce the highest amount of emissions per unit distance along the La Jolla and Mealhada corridors. These findings are in accordance with previous studies in isolated roundabouts (19, 24). Nonetheless, circulating sub-segments are shown to be emissions hotspots along the Avon and Chaves corridors. This suggests that the spacing between roundabouts could have a substantial impact on the acceleration distributions from both corridors and, consequently, in the spatial distribution of emissions. This subject is addressed and discussed in the following section.



Note: Red bar – High emission sub-segment; Green bar – Low emissions sub-segment; NS: north-south; SN: south-north; C: clockwise; AC: anti-clockwise.

Figure 3.7 Emissions per unit distance for each sub-segment across the roundabout corridor: a) CO_2 La Jolla; b) CO La Jolla; c) CO_2 Mealhada; d) CO Mealhada; e) CO_2 Avon; f) CO Avon; g) CO_2 Chaves; h) CO Chaves.

3.4.4. Spatial distribution of emissions

Table 3.3 lists the percent of time spent in each acceleration class, ranging from high decelerations (class 1) to high accelerations (class 5), in both through movements across the studied corridors. It is observed that almost vehicles do not have sharp accelerations (> 2 m/s^2) and decelerations (< -2 m/s^2). In such cases, the percent of time at any sub-segment is lower than 1%. In La Jolla and Mealhada, with equally spaced roundabouts, 21% of the acceleration time is in class 4 (between 0.2 m/s^2 and 2 m/s^2) at the downstream sub-segments. However, this percentage decreases by 4% and 7% in the Avon and Chaves corridors. Simultaneously, the time spent by vehicles in acceleration class 4 at the circulating areas of the Avon (15%) is higher than that which has been recorded in equivalent sub-segments of the La Jolla (6%) and Mealhada sites (7%). This can be explained by the fact that the circulating diameters at Avon roundabouts (on average ≈ 45 m) are higher than that in La Jolla (on average ≈ 25 m) and Mealhada (on average ≈ 37 m), as presented in **Table 3.1**. Almost roundabouts along the Chaves corridor have small size which clarify the low time spent by vehicles in acceleration class 4 (9%) at the circulating areas of that site.

Table 3.3 Acceleration class by sub-segment and by corridor

Site	Sub-Segment	Acceleration [m/s^2]				
		Class 1 [a<-2]	Class 2 [-2<a<-0.2]	Class 3 [-0.2<a<0.2]	Class 4 [0.2<a<2]	Class 5 [a>2]
La Jolla	Circulating	0.0%	5.0%	5.5%	6.1%	0.1%
	Downstream	0.0%	1.0%	5.3%	21.4%	0.0%
	Mid-block	0.0%	7.7%	12.8%	3.7%	0.0%
	Upstream	0.1%	22.6%	6.5%	2.1%	0.0%
Mealhada	Circulating	0.3%	3.7%	4.6%	6.9%	0.2%
	Downstream	0.1%	3.2%	5.7%	20.5%	0.4%
	Mid-block	0.0%	5.8%	8.2%	9.3%	0.1%
	Upstream	0.5%	21.4%	5.1%	4.0%	0.1%
Avon	Circulating	0.2%	3.5%	6.1%	14.6%	0.4%
	Downstream	0.0%	1.8%	4.9%	16.8%	0.0%
	Mid-block	0.0%	7.3%	10.1%	6.6%	0.0%
	Upstream	0.6%	20.1%	5.2%	1.6%	0.0%
Chaves	Circulating	0.3%	7.1%	5.3%	8.8%	0.5%
	Downstream	0.1%	2.2%	4.4%	14.5%	0.0%
	Mid-block	0.3%	7.2%	7.6%	7.3%	0.0%
	Upstream	0.3%	18.3%	9.7%	6.2%	0.1%

In order to complement this analysis, accelerations and CO_2 emissions distributions in each 10 m segment length are evaluated at the different sub-segments of the four corridors, as shown in **Figure 3.8**a-h. The exhibit indicates that, for all pairs of roundabouts, the spatial distribution of accelerations and CO_2 emissions is similar along the La Jolla and Mealhada corridors (**Figure 3.8**a-d). Note that the spacing between adjacent roundabouts and the entry deflection angle are similar for all roundabouts layouts. Concerning the Avon and Chaves corridors, it is clear that acceleration distributions follow different trends in each pair of roundabouts, especially in the case of closely-spaced roundabouts (RBT3 and RBT4). Hence, vehicles experience sharper accelerations at the circulating area while subsequent sub-segments (downstream, mid-block and upstream) are associated with deceleration episodes. This means that vehicles decelerate after exiting the first roundabout in proximity instead of decelerating over the mid-block. This explains the smooth variation of the CO_2 emissions curve (**Figure 3.8**e-h) between exit and yield lanes within the aforementioned roundabouts.

The main conclusion of this section is that both accelerations and emissions distributions are less impacted by entry deflection angle than spacing. This is especially noticeable for the two roundabouts in close proximity. More precisely, the RBT3 and RBT4 at Avon and Chaves have similar entry deflection angles to those measured in the RBT2 and RBT3 at La Jolla corridor (**Table 3.1**). However, in the first two study locations, the emission hot spot is found at the circulating area while in the La Jolla it is recorded at the downstream sub-segment. This suggests that the effect of entry deflection angle decreases as the spacing of roundabouts decreases, which is not observed at the isolated roundabouts (24).

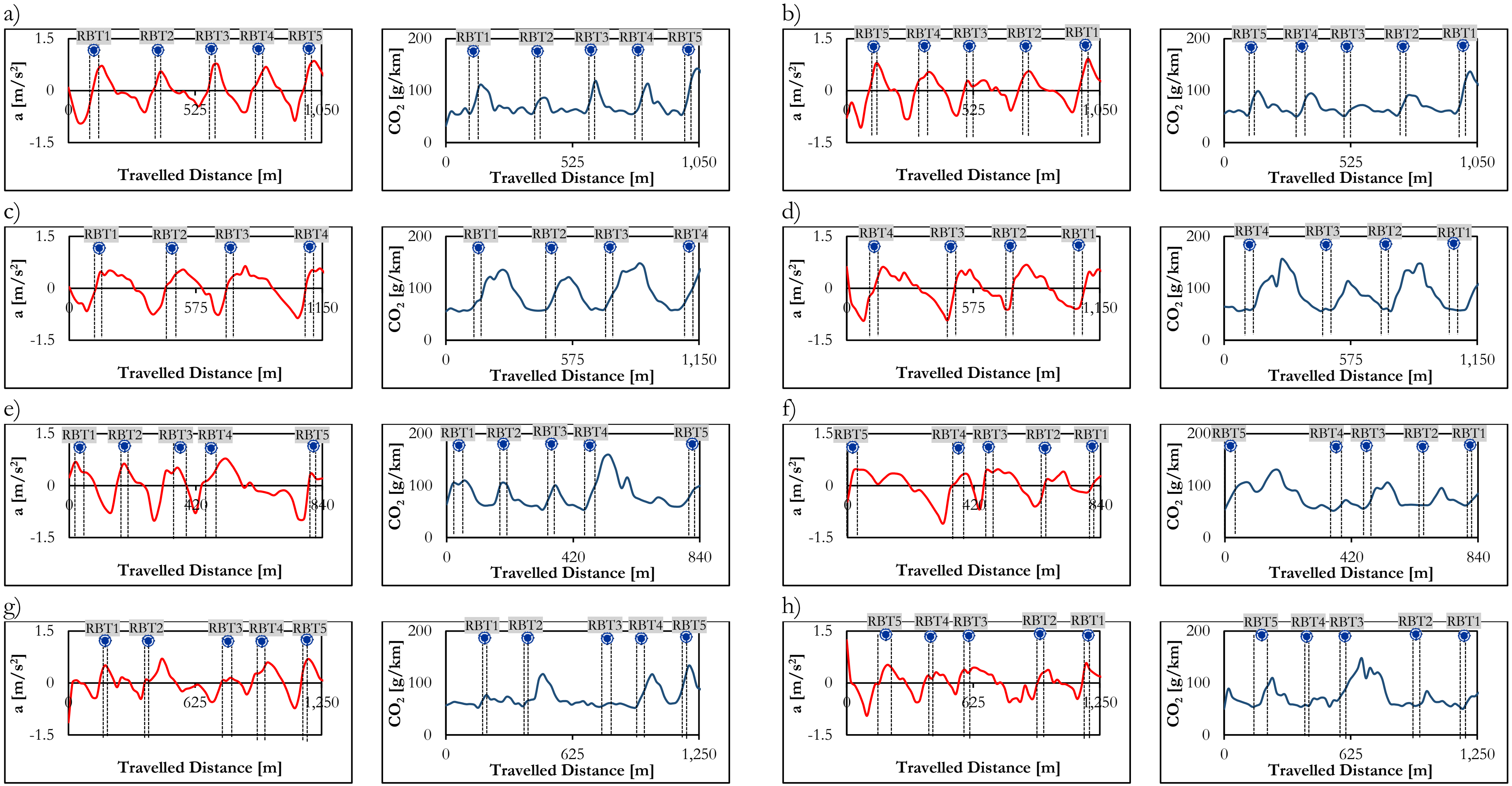


Figure 3.8 Acceleration and CO_2 distributions along the corridor: a) La Jolla (north-south), b) La Jolla (south–north); c) Mealhada (north-south), d) Mealhada (south–north); e) Avon (north-south); f) Avon (south–north); g) Chaves (clockwise); h) Chaves (anti-clockwise).

3.4.5. Relationship between emissions and corridor's design features

As noted before, the spacing between adjacent roundabouts along the corridor has a higher impact on vehicular emissions than entry deflection angle. Thus, the CO_2 and CO emissions amounts by segment are plotted against the spacing and the entry deflection angle, as depicted in **Figure 3.9**a-d. For values lower than 150 m for the spacing, vehicles generate the highest values of CO_2 and CO emissions per unit distance (**Figure 3.9**a-b). After, the values tend to be relatively constant between 150 and 350 m. The R^2 values of CO_2 and CO emissions for spacing are 0.53 and 0.41, respectively. This means that the model for CO_2 better explains the variability in the data than the model for CO. This can be explained by sharper acceleration-deceleration rates within adjacent roundabouts which have more impact on carbon monoxide emissions. In contrast, the R^2 values for the entry deflection are lower than 0.20 for both variables (**Figure 3.9**c-d). These findings are particularly relevant since they do not take into account site-specific conditions of the roundabout corridors. Also, they are in line with the results presented in previous sections.

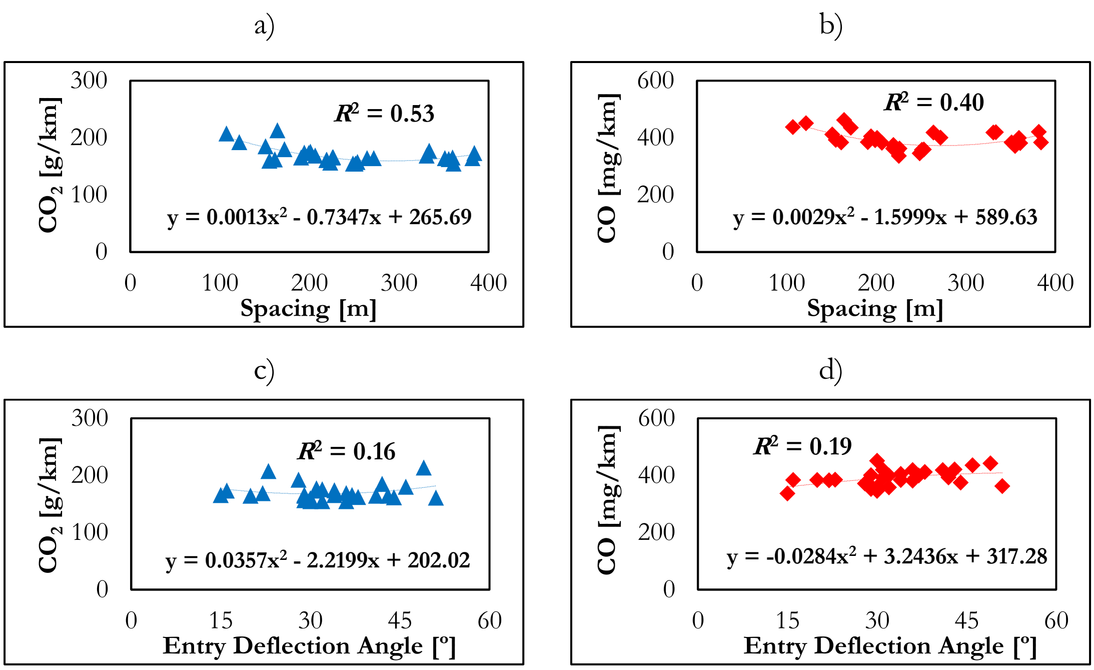


Figure 3.9 Emissions per unit distance for corridor design features: a) CO_2 versus spacing; b) CO versus spacing; c) CO_2 versus entry deflection angle; d) CO versus entry deflection angle.

3.5. Conclusions

This research introduced a methodology to measure and quantify the emissions of the different segments of functionally interdepend roundabouts on arterials. The segments considered were the circulating area of each roundabout, downstream, mid-block and upstream between adjacent roundabouts. The paper also identified the emission hotspots along the corridor, either in absolute terms as per unit distance. To accomplish the objectives posed, four corridors with roundabouts exhibiting similar design features (posted speed limit, total corridor length, low spacing between adjacent roundabouts and traffic flows), but a different interspacing of roundabouts (two corridors with equally spaced roundabouts and two with unequally spaced roundabouts) were selected. For emissions estimation, a methodology based on vehicle specific power was used.

It was concluded that the emissions distributions along the corridors with equally spaced roundabouts and enough spacing to attain cruise speed over the mid-block was similar for each pair of adjacent roundabouts. In such cases, the downstream sub-segments were identified as the emissions hotspots (overall contribution on total emissions exceeded the 34%) both in absolute terms and per unit distance. Considering the corridors with unequally spaced roundabouts, the CO_2 and CO emissions hot spots per unit distance, about 9% higher than the average corridors values were found at the circulating areas sub-segments. This was particularly true for closely spaced roundabouts (<165 m of spacing) in which vehicles decelerated after the roundabout exit section (at the downstream sub-segment). The evaluation of CO_2 and CO emissions for different values of spacing and deflection angle pointed out to the higher impact of spacing on emissions along corridors ($R^2 > 0.40$). In contrast, a slight impact of deflection on emissions was noted ($R^2 < 0.20$). The findings of the paper suggest that the impact of entry deflection angle on acceleration profiles and so that in emissions decreases for low roundabout's spacing. This aspect is not verified on isolated roundabouts and must be taken into account for design considerations of roundabouts in sequence in a corridor.

The main limitation of this paper is the small sample size of the corridors that were chosen for this analysis. The second limitation is the similar approach and free-flow speeds as well as traffic flows for the four roundabouts studied for this research. It should be also referred that the equality in spacing between adjacent roundabouts does not mean that emission hotspots are attributed to downstream areas. In spite of being a moderate roundabout spacing (ranged from 190 m to 350 m), the selected corridors worked as five (La Jolla) and four (Mealhada) isolated roundabouts. In the hypothetic case of low roundabouts spacing, as was the case of Avon or Chaves corridors (e.g. 100 m), the impacts of downstream and mid-block decrease since vehicles are not able to attain higher speeds. Consequently, the vehicle activity data among downstream, mid-block and upstream is affected.

Therefore, future work is needed, namely: the study of other corridors with different spacing between adjacent roundabouts (extreme low and high interspacing of the roundabouts), roundabouts layouts (e.g. turbo-roundabouts) and the impact of traffic flows and free-flow speed along the corridor on the spatial distribution of emissions.

3.6. Acknowledgments

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4. ASSESSMENT OF CORRIDORS WITH TRADITIONAL TYPES OF INTERSECTIONS

Previous chapter confirmed that downstream (acceleration) and circulating areas segments and spacing between roundabouts influenced emissions along corridors. However, the type of intersection within a corridor can dictated different emissions impacts according to the site-specific characteristics. In this chapter, a modeling traffic tool is used to simulate traffic operations from an existing corridor with four single-lane roundabouts, and compare its traffic performance and emissions against equivalent signalized corridors and stop-controlled intersections for two demand levels.

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Abstract

Recently, roundabouts in a series have been installed along corridors to enhance road safety. However, the benefits of this traffic-calming technique on traffic performance and pollutant emissions compared with other forms of intersections, such as traffic lights and stop-controlled solutions, are not properly known. This study used a microscopic approach to evaluate the effects of a corridor with four roundabouts on traffic performance and emissions, in comparison with traffic lights and stop-controlled solutions. Average travel time and number of vehicle stops were used as measures of traffic performance; carbon dioxide, monoxide carbon, nitrogen oxides, hydrocarbons, and particulate matter were used to quantify emissions. The traffic and emissions performance of each solution was evaluated on three levels: (*a*) arterial, (*b*) intersection, and (*c*) morning peak versus evening peak periods.

It was found that, regardless of the demand period, traffic lights in corridors at the arterial level produced higher total emissions (> 6%), while stop-controlled intersections produced lower emissions (≈12%) compared with roundabouts, mainly because of unbalanced traffic flows between main and minor roads. The results for traffic performance showed advantages in implementing roundabouts when the main concern was the number of vehicle stops. At the intersection level, an emissions improvement (between 2% and 14%) was observed at traffic lights on four-leg intersections.

Keywords: Corridors; Intersections; Roundabouts; Traffic Lights; Traffic Performance; Emissions

4.1. Introduction and Research Objectives

The number of roundabouts constructed worldwide has grown in the past years. As a result, some local authorities have recently approved and constructed the use of a series of roundabouts in corridors, rather than the traditional solution of coordinated traffic lights. The renewed interest in their implementation can be attributed to the improved safety features of roundabouts that allow reducing vehicle speed (1).

Nevertheless, quantitative and qualitative information on the environmental performance of a set of functionally interdependent roundabouts on corridors is lacking (2). A typical question concerning the use of corridors with roundabouts is how traffic will perform. The main goal along a corridor with traffic lights is to coordinate lights to ensure good progression, so that vehicles can travel through the arterial with a minimum number of stops. A series of roundabouts forces all vehicles to slow down at every roundabout, causing several acceleration-deceleration cycles and, as consequence, higher emissions and greater fuel consumption. This is particularly true in downstream areas (3).

Extensive research has dealt with how isolated roundabouts compare with all-way stop control, two-way stop control, and traffic lights in the field of energy and emissions, but the results are not in agreement about the benefits. Some studies have shown that roundabouts have led to higher emissions and fuel consumption than two-way stop-controlled intersections (4) or traffic lights (5). In contrast, other studies have suggested that the environmental and energy performances of roundabouts are largely dependent on traffic flows, depending on the approaches and turning demands. Coelho et al. (6) confirmed that fixed-cycle traffic lights caused more emissions than a roundabout (considering a conflict flow of 750 vehicles per hour – vph) for higher traffic flows. Vlahos et al. (7) explained that, compared with a traffic signal, the roundabout performed environmentally better with traffic flow compared with all of the approaches at 2,300 vph. Rakha and Jackson (8) demonstrated that roundabouts recorded less fuel consumption and carbon dioxide (CO_2) emissions than all-way stop control, two-way stop control, and traffic lights when left-turn demands were below 30%. Rakha et al. (9) indicated that both single-lane and two-lane roundabouts outperformed the one-way stop-controlled intersection in a three-way intersection in a study of carbon monoxide (CO) emissions and delay. However, one-way stop-controlled intersections were associated with fewer hydrocarbons (HC), nitrogen oxides (NO_X) and CO_2 emissions. Anya et al. (10) investigated the benefits posed by the conversion of a signalized intersection to a two-lane roundabout. They concluded that, at the intersection-level, the reduction in emissions was only relevant in the right-turn movements from the minor to the main road. Gastaldi et al. (11) found that the environmental benefits of a four-leg roundabout, compared with a fixed-time traffic signal, were smaller than the roundabout's operational performance.

Several researchers have investigated and developed algorithms for signalized arterials to minimize emissions and fuel consumption along corridors (12, 13). The few studies carried out for corridors with roundabouts raised some uncertainties about their effectiveness. Hallmark et al. (14) recorded marginal benefits in improved traffic flow of roundabouts in signalized corridors over stop- and signal-controlled intersections. Hallmark et al. (15) studied on-road emission impacts of roundabouts with a stop intersection compared with roundabouts with signal-controlled intersections along two corridors. The findings suggested that, under uncongested conditions, roundabouts did not perform better than four-way or signal-controlled intersections in the same corridor. However, each studied corridor (14, 15) only contained one roundabout throughout its length (series of roundabouts were not considered). Krogscheepers and Watters (16) assessed the average speeds, delay, and travel time of six roundabouts along a rural corridor in South Africa and compared the results with fixed-cycle traffic lights. The authors concluded that roundabouts offered operational advantages over traffic lights, but recognized that roundabouts became inefficient when the levels of demand increased. More recently, a study conducted on 58 US roundabout corridors developed a methodology for estimating travel speed and level of service (LOS) (2). Although these studies developed very good traffic analysis, they did not include an analysis of emission impacts (2, 16).

Considering the foregoing discussion, the main motivation for this study can be outlined in two main points. First, there is a need for a suitable methodology to estimate the emissions impacts from a series of roundabouts along corridors. Second, although there is an extensive knowledge on traffic operations at isolated roundabouts rather than in sequence, there is a lack of studies comparing the emissions benefits of corridors with different intersection types. There is a concern that under specific traffic conditions (which are associated with the variability of traffic during the day and geometric features of the roundabouts), the operational and environmental benefits may be lower than expected.

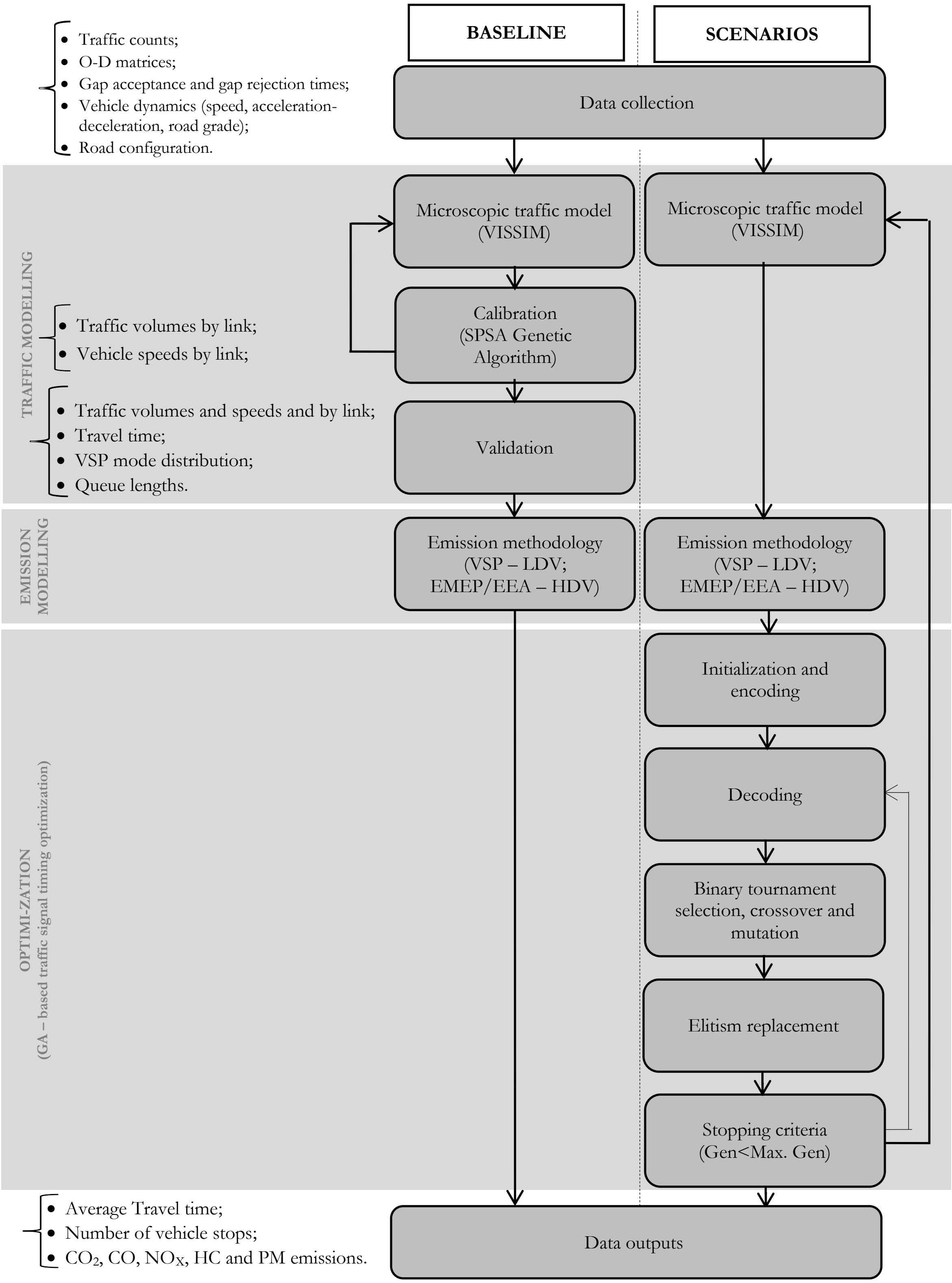
The principal objective of this study was to compare the traffic performance and emissions of a roundabout corridor with an equivalent corridor where roundabouts are replaced by traffic lights and stop-controlled intersections. The study used a microsimulation approach to evaluate scenarios at different analysis levels (arterial and intersection levels) and time periods (morning and evening peak periods). To analyze these impacts, the proposed approach integrated the VISSIM microscopic traffic model and the Vehicle-Specific Power (VSP) and European Monitoring and Evaluation Programme by European Environmental Agency (EMEP/EEA) emissions methodologies. A genetic algorithm (GA) was used to optimize the traffic signal timing at arterials on emissions.

The novelty of this research, compared with others studies of roundabout corridors (2, 16) and corridors composed of a roundabout with other intersection forms (14, 15), is that the study compares both traffic performance and emissions among various corridor layouts. An integrated methodology was used, based on a microscopic simulation approach from vehicle activity and traffic flow data simultaneously. The focus was on the following research questions:

- How do traffic performance and emissions vary during morning and evening peak hours for corridors with roundabouts and other forms of intersections?
- How do the design features of a corridor affect the spatial distribution of emissions?

4.2. Methodology

The main goal of the proposed methodology was to develop a microscopic simulation platform on traffic and emissions (**Figure 4.1**). This platform enables the analysis of other impacts of capacity and emissions for corridors with roundabouts, traffic lights, and stop-controlled intersections. **Figure 4.1** depicts the basic structure of the GA-based traffic signal optimizer used in this research. The following sections present a detailed description of the methodological steps.



Legend: SPSA - Simultaneous Perturbation Stochastic Approximation; LDV - Light Duty Vehicle; HDV - Heavy Duty Vehicles; PM - Particulate Matter; GA - Genetic algorithm; O-D - Origin-Destination; Gen - number of generations; Max. - Maximum

Figure 4.1 Summary of methodological steps.

4.2.1. Data Collection

An urban corridor with four single-lane roundabouts, exhibiting high traffic flows, was sought out for this research. The free-flow speed was fairly constant along this corridor and the spacing was approximately equal between adjacent roundabouts (the coefficient of variability of average spacing was 0.11). The corridor is approximately 1,466 m (4,810 ft.) long and includes two roundabouts with four legs (RBT1 and RBT3) and two roundabouts with three legs (RBT2 and RBT4). The posted speeds on the approach legs are ≈30 km/h. **Figure 4.2** and **Table 4.1** summarize the information regarding on the site's characteristics.

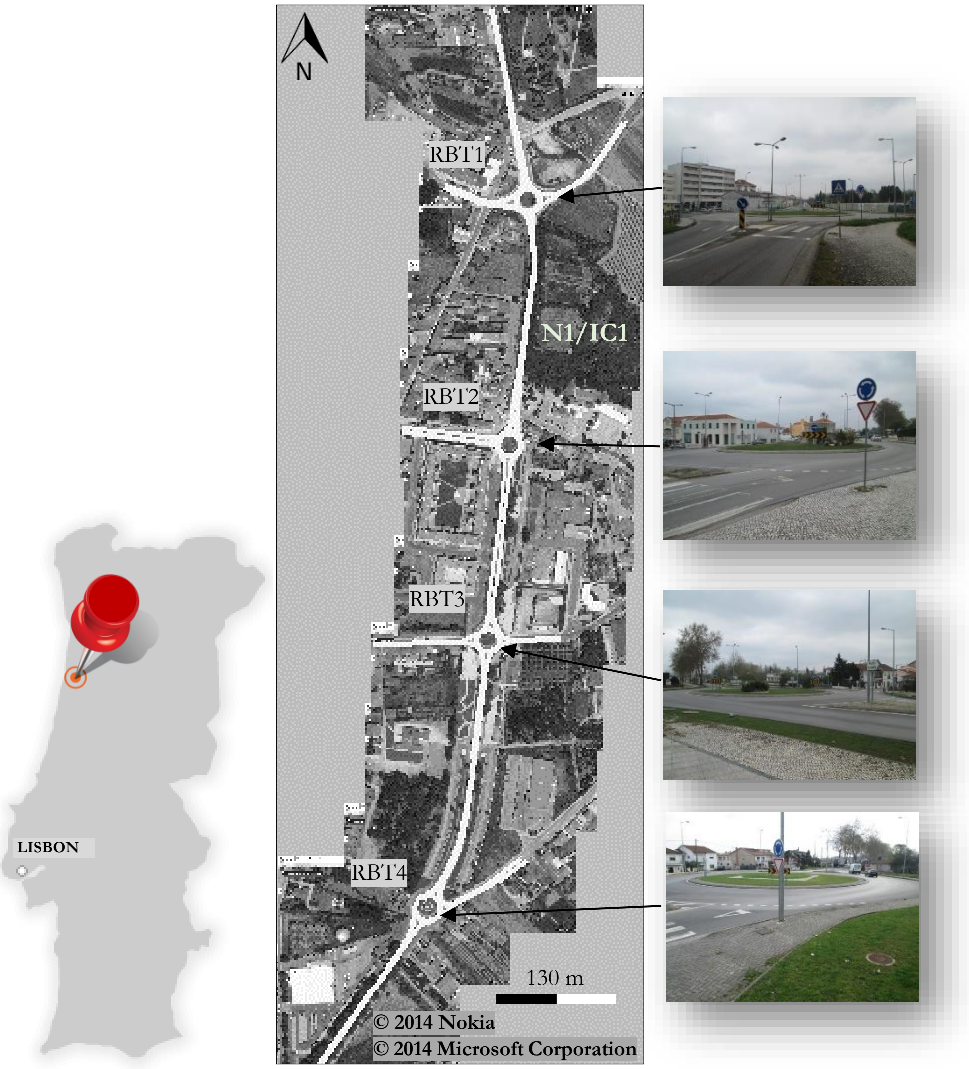


Figure 4.2 Aerial view of the selected corridor with the roundabouts identification (RBT1, RBT2, RBT3 and RBT4) (Mealhada, Portugal).

Table 4.1 Key characteristics of the selected corridor

ID	Entry speed		Central Island [m (ft.)]	Circulating Width [m (ft.)]	Distance from upstream roundabout [m (ft.)]	Average roundabout spacing [m (ft.)]
	north-south [km/h (mph)]	south-north [km/h (mph)]				
RBT1	29.4 (18.3)	24.7 (15.3)	25 (82)	7 (23)	NA	303 (994)
RBT2	21.3 (13.2)	30.2 (18.8)	24 (79)	8 (26)	318 (1,043)	
RBT3	27.9 (17.3)	26.1 (16.2)	23 (75)	7 (23)	255 (836)	
RBT4	27.5 (17.1)	26.8 (16.7)	28 (92)	7 (23)	335 (1,099)	

Notes: *ID - identification; RBT - roundabout; NA - not applicable.*

CV – Coefficient of Variability (ratio between standard deviation of average roundabout spacing and average roundabout spacing).

During a typical weekday, traffic counts suggested that morning and evening peak periods occur between 7:00-9:00 a.m. and 4:00-6:00 p.m., respectively. Thus, the following data were collected at the selected corridor for these periods in April 2014:

- Traffic flow of Light Duty Vehicles (LDV), transit buses and Heavy Duty Vehicles (HDV);
- Time-Dependent Origin-Destination (O-D) matrices;
- Gap acceptance data; and
- Vehicle activity data (speed, acceleration-deceleration and grade).

Traffic and time-dependent O-D matrices were gathered from overhead videos installed at strategic points of the roundabouts. The traffic data were recorded at morning and evening periods for six days on typical weekdays (Wednesday and Thursday) during three weeks under dry weather conditions. Later, in the transportation laboratory, the traffic data for each vehicle class were compiled to define O-D tables based on trips along the whole corridor for each vehicle class. Time-gap distributions data (gap-acceptance and gap-rejection) were also extracted from the videotapes.

For vehicle activity estimation, second-by-second vehicle dynamics data were recorded. An LDV and HDV, equipped with a GPS Travel recorder, were used to perform several movements along the corridor. For each movement, 200 GPS travel runs were extracted and identified (approximately 400 km of road coverage over the course of 8 h).

As shown in **Table 4.2**, the corridor primarily serves through traffic (northbound and southbound). The average number of vehicles entering each roundabout were approximately 1,380 to 1,430 (vph) for the morning and evening peak hours, respectively. The corridor is characterized by high demand of HDV, ranging from 9% to 14%. It was perceived that the traffic data between adjacent roundabouts was relatively similar along the corridor in both the morning and evening peak periods. However, the corridor had spare capacity in both time periods. All roundabouts had a critical movement volume-to-capacity ratio (v/c) of 0.85 or less.

Table 4.2 Average volume observations (LDV and HDV) at data collection corridor during morning and evening peak hours of the selected corridor

Period	ID	Approach volume N [vph]	Approach volume S [vph]	Approach volume W [vph]	Approach volume E [vph]	% HDV [% Total traffic]	Arterial volume [vph[a]]	Critical Intersection [v/c ratio[b]]
Morning (8-9 a.m.)	RBT1	469	598	265	279	10.3%	970	0.85
	RBT2	505	712	120	NA	12.5%	1,103	0.84
	RBT3	477	624	79	121	12.8%	1,189	0.78
	RBT4	497	669	NA	91	13.6%	NA	0.77
Evening (5-6 p.m.)	RBT1	501	590	275	261	9.5%	998	0.83
	RBT2	543	725	105	NA	9.7%	1,012	0.83
	RBT3	544	632	90	105	9.4%	1,269	0.75
	RBT4	563	683	NA	95	10.1%	NA	0.70

Legend: *N - northbound; S - southbound; W - westbound; E - eastbound; NA - not applicable.*

Note: *Traffic demand in the evening peak is approximately 3% higher than in morning peak period.*

[a]*Arterial volume between actual roundabout and upstream roundabout (in south direction);*

[b]*Based on preliminary traffic analysis.*

4.2.2. Scenarios

The Baseline scenario is the validated model for the morning and evening peak periods (**Figure 4.2**). To assess the traffic performance and emissions of corridors with different series of intersection types, two scenarios were established:

- Scenario 1 (S1): All roundabouts were replaced by traffic lights; and
- Scenario 2 (S2): RTB1 and RBT3 were replaced by two-stop controlled intersections (west and east approaches), and RBT2 and RB4 were replaced by one-stop controlled intersection (west and east approaches).

To model traffic lights, separated left and through lanes from main approaches (north and south) were used. Similarly, a lead-lead left-turn phase sequence was considered, as shown in **Figure 4.3**. The advantages of this phasing option were: (*a*) drivers react quickly to the leading green arrow indication; and (*b*) it reduces conflicts between left-turn and through movements on the same approach (17). Furthermore, the safety between conflicting traffic was not affected significantly, since the selected corridor has low left-turning rates from the main approaches. A yellow time of 3 s was assumed in this study.

The emissions and traffic performance of each traffic scenario were evaluated on three levels: *a*) arterial; *b*) intersection; and *c*) morning versus evening peak periods. For consistency with Rodegerdts et al. (2), influence areas were defined to conduct the intersection-level analysis. For this study, the same influence area among scenarios was considered. Average travel time and number of stops were used as measures of traffic performance; CO_2, CO, NO_X, HC and particulate matter (PM) emissions were used as emissions measures.

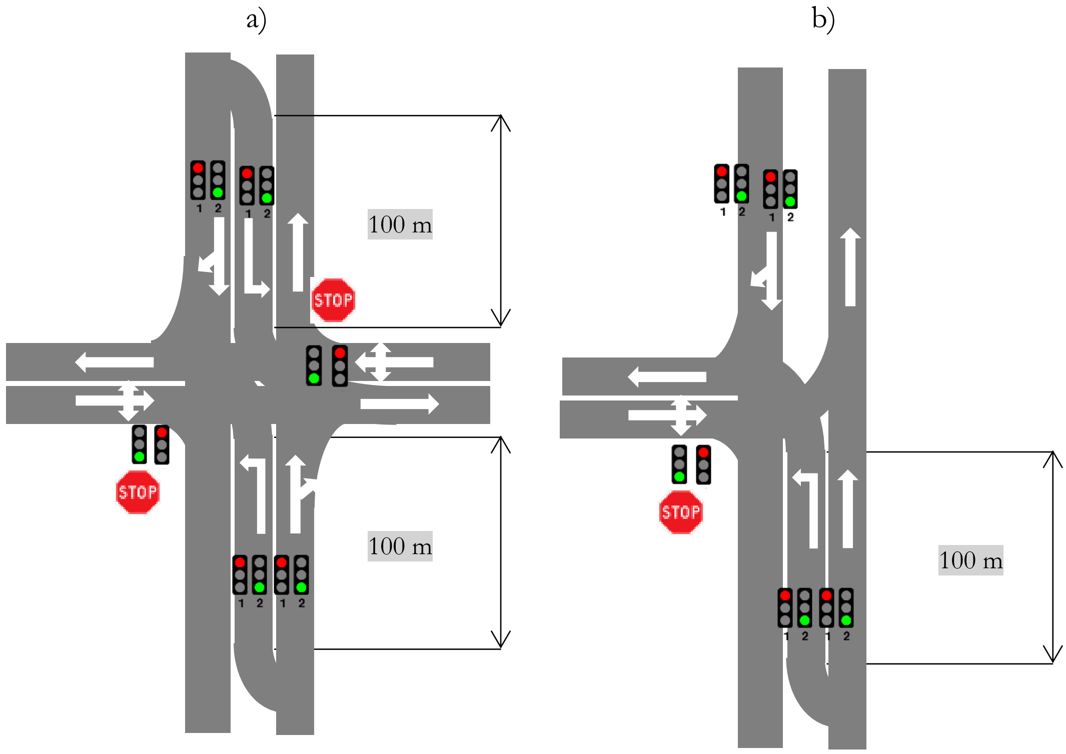


Figure 4.3 Layout of intersections with traffic lights (including phasing) and stop-controlled: a) four-legs; b) three-legs (1 is red signal; 2 is green signal).

4.2.3. Modelling Platform

4.2.3.1. Road traffic modelling

The VISSIM microsimulation model (18) is extensively recognized as a powerful tool for operational analysis of corridors with different types of intersections (14). VISSIM can be calibrated to set faithful representations of the traffic, especially at capacity (19), and faithful assessments of emissions in urban areas (20). VISSIM allows exporting trajectory files that can be used by external emission models.

The simulation model was run for 90 min (7:30-9:00 a.m. and 4:30-6:00 p.m.), with the first 30 min used for a warm-up period. Data were extracted only for the remaining 60 min (8:00-9:00 a.m. and 5:00-6:00 p.m.). Since transit buses represented less than 0.2% of traffic composition, they were excluded from the analysis. Two O-D matrices for LDV and HDV were generated per 15 min for periods between 7:30-9:00 a.m. and 4:30-6:00 p.m.

The treatment of the yield areas used the Priority Rules tool of the VISSIM model (18). For the analysis, the same minimum gap time and headway distance in each one of the yield areas was considered.

Model consistency of the corridor with roundabouts was focused on two main steps: calibration and validation. Calibration was made by modifying the driver behavior parameters of the traffic model and examining their effect on traffic volumes and speed for each link. The main driver behavior parameters were divided into car-following parameters (average standstill distance and additive and multiple parts of safety distance), lane-change parameters, gap acceptance parameters (minimum gap time and headway distance), and simulation resolution (18).

A procedure based on the Simultaneous Perturbation Stochastic Approximation (SPSA) genetic algorithm was used to optimize the aforementioned model parameters. The objective function was based on the minimization of Normalized Root Mean Square (NRMS) (**Eq. 4.1**). NRMS is defined as the sum over the two calibration periods of the average of the sum over all links of the root square of the normalized differences between observed and estimated parameters (21). The normalization enables the consideration of several performance measures simultaneously, in this case, link volumes and vehicle speed. The calibration procedure is posed as follows:

$$\text{Min } NRMS = \frac{1}{\sqrt{N}} \times \sum_{t=1}^{T} \left(W \times \sqrt{\sum_{i=1}^{I} \left(\frac{v_i - \tilde{v}(\theta)_i}{v_i} \right)^2} + (1-W) \times \sqrt{\sum_{i=1}^{I} \left(\frac{s_i - \tilde{s}(\theta)_i}{s_i} \right)^2} \right) \quad \textbf{Eq. 4.1}$$

Subject to: Lower bound ≤ θ ≤ Upper bound

Where:

N = Total number of links in the coded network;
T = Total number of time periods t;
W = Weight to assign more or less value to volumes or speeds;
I = Last analyzed link;
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.

For the calibration criteria, the widely accepted practice is to rely on the Geoffrey E. Havers (GEH) statistic for assessing goodness-of-fit. The difference between observed and estimated link volumes should be less than 4 for at least 85% of the coded links (22). Lastly, queue lengths at entry roundabouts were also compared with the default and calibrated values.

The model validation was focused on the comparison between estimated and observed volumes, speeds, travel time, and VSP mode distributions for a preliminary number of simulation runs [between 10 and 20, as suggested by Hale (23)]. Validation criteria for volumes, speeds, and travel time were undertaken using GEH statistic (22) and root mean square percentage error (RMSPE) (24).

To examine the discrepancy between the estimated and observed VSP mode distributions, the two-sample Kolmogorov – Sminorv test (K–S test) for a 95% confidence level was employed. More information about this validation procedure can be found in Fontes et al. (20). About 80% of the data collected were used for calibration; the remaining data were used for validation.

4.2.3.2. Emission modelling

The methodology used to estimate emissions was based on VSP (25, 26), which is based on regression models and allows characterizing the vehicle activity data on a second-by-second basis. The VSP values are categorized in 14 modes of engine regime and an emission factor for each mode is used to estimate CO_2, CO, NO_X and HC emissions from Light Duty Gasoline Vehicles (LDGV) with engine size <1.2l (10, 25, 26), Light Duty Diesel Vehicles (LDDV) <1.6l (27), and Light Commercial Diesel Vehicles (LCDV) <2.5l (27). VSP has been shown to be a useful explanatory variable for estimating variability in emissions, especially for CO, CO_2 and NO_X (28, 29). The EMEP-EEA methodology was used for HDV emissions and PM emissions from all vehicle types (30). This methodology is based on average values of speed, slope and load factor. Different emissions factors are available depending on the age and engine capacity of each vehicle class and fuel type.

For both methodologies the following distribution fleet composition was considered for LDV (31): 44.7% of LDGV, 34.3% of LDDV and 21.0% of LCDV. Since the study corridor was located on relatively flat grades (<1%), the effect of that parameter was ignored.

4.2.3.3. Traffic signal timing optimization

The GA-based traffic signal optimizer was applied to optimize vehicular emissions (CO_2, CO, NO_X, HC and PM). The GA is a stochastic search technique based on the mechanics of natural selection and evolution (32). The Fast Non-Dominated Sorting Genetic Algorithm (NSGA-II) was adopted in this case (33) (**Figure 4.1**). The analysis used the following traffic timing plan optimization variables (according to the corridor characteristics) with the corresponding range values:

- Cycle: 40 to 120 s;
- Offset between adjacent intersections: 8 to 24 s; and
- Green time at minor streets: minimum of 10 s.

The optimization of the traffic signal timing was performed separately for the two peak periods. NSGA-II code includes binary and real number encodings (33). Thus, a binary encoding technique was employed for the NSGA-II coding scheme. Further, NSGA-II interprets individual chromosomes represented in binary strings of 0 and 1, as optimization variables. For cycle length, green times, and offsets, a fraction-based decoding scheme was applied, as in Kwak et al. (34). Before performing the GA operations, the potential traffic signal timing plans were evaluated by running the road traffic and emissions.

NSGA-II uses a tournament selection approach, which has shown good performance in traffic signal timing plan optimization (33). In this step, better traffic signal plans have higher chances of being selected. Then, a crossover operation based on a procedure to compose a mating pool and create a new population for the next generation is performed. After that, a uniform crossover is applied for each pair of chromosomes from the tournament selection in which individual bits are compared between two chosen chromosomes, and the compared bits are replaced with a 0.5 probability. A mutation operator changes single bits of chromosomes when each bit satisfies the mutation probability of 0.03. These probabilities are recognized to be effective for traffic signal timing plan optimization (34).

4.3. Results

4.3.1. Model Evaluation

Figure 4.4 exhibits the observed and estimated traffic volumes and vehicle speeds before (with VISSIM default values) and after the calibration of the traffic model for the morning and evening periods. The results confirm larger improvements for vehicle speeds, while traffic volumes were only slightly modified.

After the calibration, the speeds improved for 61% (n = 41) and 62% (n = 42) of the links in the morning and evening peak periods, respectively, while the remaining values were similar to the initial values. Moreover, R^2 values greater than 0.90 for the estimated parameters, versus observed parameters, were recorded for the calibration procedure.

Table 4.3 summarizes the traffic calibration and validation results obtained for the NRMS and GEH statistics, queue length, and VSP modes distribution. The lane-change parameters and simulation resolution are unaffected by the calibration. In the first case, all coded links have one lane. In the second case, a value of 10 time steps per simulated second was used to fit the time resolution of the traffic and emission models (a second-by-second basis). It was demonstrated that the calibrated model parameters improved the GEH statistic, that is, all the links achieved a GEH statistic less than 4, thereby satisfying the calibration criteria. The NRMS went from 0.47 to 0.29 in the morning peak and from 0.45 to 0.28 in the evening peak. It was also found that default values underestimated speed values and yielded larger queues at entry areas (>15% compared with observed data).

This finding means that initially some of the traffic model behavior parameters did not properly represent the site-specific traffic operations, and possibly some of the values were relatively high. This was particularly true in the case of stand-still and headway distance, for which the decrease was 60% and 40%, respectively, in relation to the default values. The difference between observed and estimated values of queue lengths (>6% with calibrated values) confirmed the correctness of the above calibrated driver behavior parameters. Similarly, the calibrated minimal gap time was close to those obtained from the field measurements (3.0 s), which reflects Portuguese driving habits (35).

For the validation results, the comparison of observed and estimated flows and travel time was conducted with a different data sample from the calibration and an additional 15 random seed runs (23). The runs showed that more than 85% of the coded links recorded GEH values below 4 and RMSPE below 20%. The analysis of VSP modes distribution indicated that 67% (n = 45) and 100% (n = 64) of the coded links did not show significant differences at a 95% and 99% confidence levels, respectively, considering the evening peak conditions. These validation results suggest a very good degree of consistency for all cases (22, 24). The resulting validation settings were subsequently applied to all scenarios.

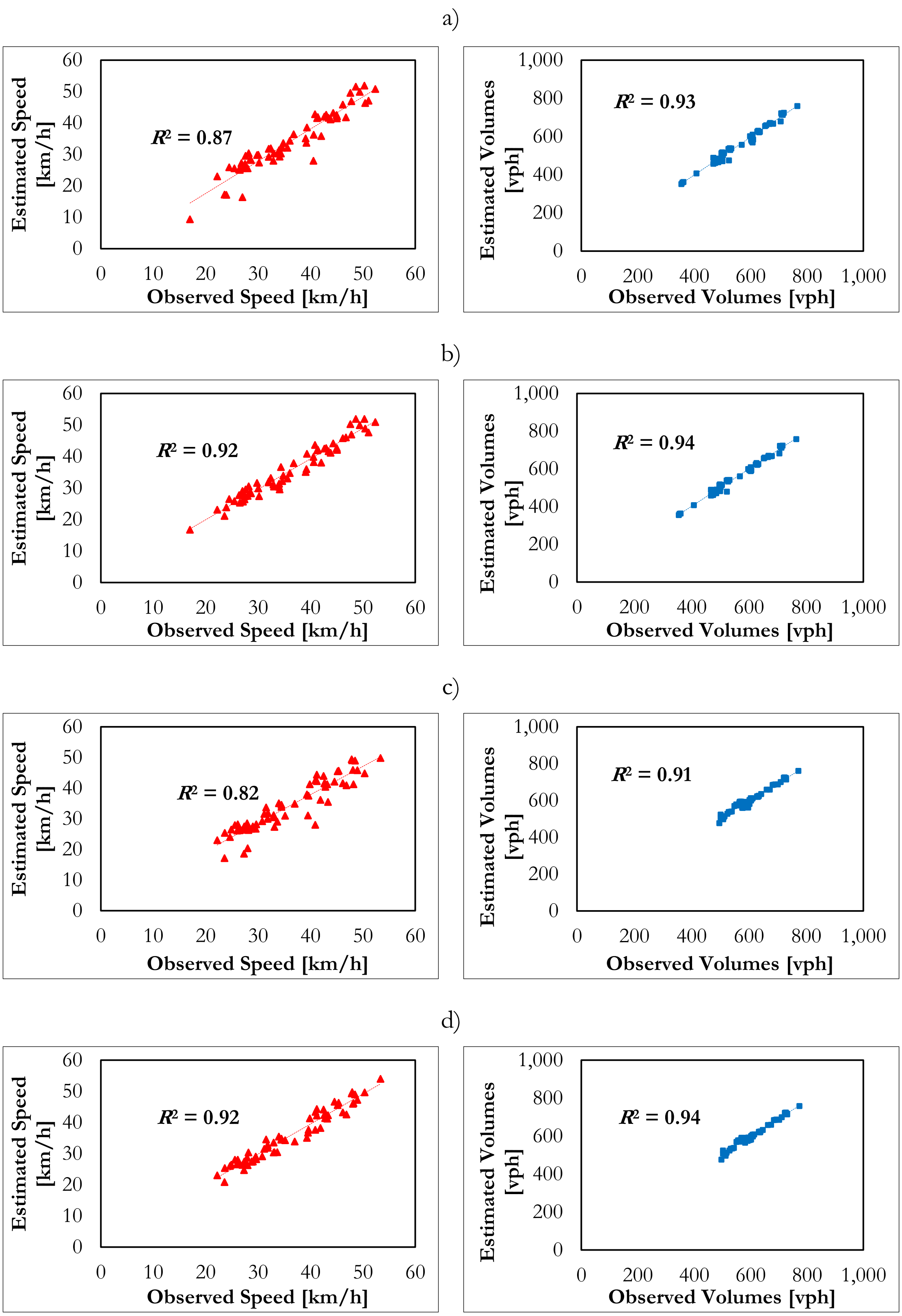


Figure 4.4 Observed versus Estimated speed and traffic volumes: a) Default parameters for morning peak; b) Calibrated model for morning peak; c) Default parameters for evening peak; d) Calibrated model for evening peak.

Table 4.3 Summary of calibration and validation results for the traffic model

Period	Model	Parameter	Value	Morning			
				NRMS	GEH	Queue length	VSP Modes
Morning	Default	Average standstill distance (m)	2.0	0.469	< 5 for 98 % of the cases	≈ 17% higher than field data	50% and 90% of the links not statistically significant at a 95% and 99% CI
		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	Average standstill distance (m)	0.8	0.285	< 5 for 100 % of the cases	≈ 7% higher than field data	72% and 100% of the links not statistically significant at a 95% and 99% CI
		Additive part of safety distance	1.3				
		Multiple part of safety distance	1.5				
		Minimal gap time (s)	2.7				
		Minimal headway (m)	4.5				
	Validated	Average standstill distance (m)	0.8	0.401	< 5 for 87 % of the cases	≈ 8% higher than field data	70% and 100% of the links not statistically significant at a 95% and 99% CI
		Additive part of safety distance	1.3				
		Multiple part of safety distance	1.5				
		Minimal gap time (s)	2.7				
		Minimal headway (m)	4.5				
Evening	Default	Average standstill distance (m)	2.0	0.451	< 5 for 96 % of the cases	≈ 20% higher than field data	46% and 91% of the links not statistically significant at a 95% and 99% CI
		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	Average standstill distance (m)	0.8	0.281	< 5 for 100 % of the cases	≈ 8% higher than field data	70% and 100% of the links not statistically significant at a 95% and 99% CI
		Additive part of safety distance	1.3				
		Multiple part of safety distance	1.5				
		Minimal gap time (s)	2.7				
		Minimal headway (m)	4.5				
	Validated	Average standstill distance (m)	0.8	0.393	< 5 for 90 % of the cases	≈ 9% higher than field data	67% and 100% of the links not statistically significant at a 95% and 99% CI
		Additive part of safety distance	1.3				
		Multiple part of safety distance	1.5				
		Minimal gap time (s)	2.7				
		Minimal headway (m)	4.5				

Legend: *- CI – Confidence Interval*

Note: - *The weight factor (W) was set to 0.7; Model was validated with 15 random seed runs.*

4.3.2. Model Traffic performance measures and emission rates

This section compares the emissions and traffic performance parameters of the two scenarios with the Baseline scenario. The average values of the optimizing parameters became stable after 50 generations indicating that NSGA-II converges. Thus, the following parameters were used in the corridor with traffic lights in the morning and evening peak periods, respectively: cycle: 45s and 41s; offset: 19s and 12s; and green time at minor streets: 12s and 10s. The emissions and traffic performance impact results are presented in **Table 4.4** by analysis-level and scenarios for the morning, evening, and aggregate time periods. Key observations from the data in **Table 4.4** are as follows:

- Considering the overall corridor and morning peak hour, significant differences between S1 and the Baseline were observed (vehicles produce an average amount of additional emissions of 7% in S1); S2 gave lower emissions in the arterial-level analysis, mainly for CO_2 and HC, with reductions of 12% and 13%, respectively, but was ineffective in idling situations (increase of 7% in the number of stops);
- S2 was the best environmental solution in the evening peak period. It had average emissions reductions of about 12% and yielded the smallest travel time of 16%. There were slight differences between the environmental performance of the Baseline and S1 compared with the morning peak conditions;
- For the intersection-level analysis and morning peak conditions, the findings pointed out considerable differences, especially among scenarios during the morning peak period (all pollutants increased between 14% and 19% with S1, while the number of stops increased by more than 30%). However, the RBT4/I4 in S1 had better environmental performance than the roundabouts (8% to 10%, depending on the pollutant). There were decreases in emissions of about 25% for CO_2, CO, and HC for the RBT4/I4 in S2;
- In the intersection-level analysis with evening peak conditions, S2 provided a significant advantage in traffic operations at four-leg intersections, compared with the alternative of a roundabout (6% and 9% less emissions in RBT1/I1 and RBT3/I3, respectively). S1 presented the highest number of vehicle stops and amounts of emissions at those intersections, but average emissions (5% to 14%, depending on the pollutant) and travel time (<6%) decreased at the three-leg intersections, compared with the roundabouts. S2 achieved significant reductions in emissions at the RBT4/I4 (its implementation allowed CO_2 and average travel time to be reduced by 25% and 19%, respectively);
- Considering the aggregate contribution of the two periods, S2 also gave the best emissions scenario in the arterial-level analysis (-12% of CO_2 compared with the Baseline). S1 and the Baseline emitted the highest amount of CO_2 at the four-leg and three-leg intersections, respectively.

In summary, comparison of the layouts of the corridors revealed different results between roundabouts and traffic lights. In some situations, S1 and S2 achieved lower travel time and higher stop-and-go situations, compared with roundabouts. This point was explained by the high travel time on minor roads (caused by longer red times and the obligation to come to a complete stop at the intersection). Similarly, travel time was compensated on the main roads, since the most of the traffic goes through. Also, vehicles made left turns from the main roads to the minor roads, first stopping and waiting for a gap in the opposite through movement. In roundabouts, vehicles do not always perform complete stops, since most of the conflicting traffic comes from minor roads. These traffic performance findings were also found by Krogscheepers and Watters (16).

This research suggests that some segments of the corridor with roundabouts have a relevant impact on speeds and the spatial distribution of emissions. Consequently, it is important to understand how design features of the corridor affect vehicle dynamics and emissions. This subject is addressed and discussed in the following section.

Table 4.4 Variation of emissions and traffic performance parameters per location in relation to the Baseline scenario, during the morning peak hour (8:00-9:00 a.m.), evening peak hour (5:00-6:00 p.m.) and two time periods

Period/	Area	Scenario	Emissions					Traffic Performance		
			CO_2 (kg)	CO (g)	NO_X (g)	HC (g)	PM (g)	Traffic Flows	Travel Time (s/veh)	Total stops
Morning peak	OC	Baseline	1,648	51,333	9,317	756	455	2,168	58.8	851
		S1	8%	8%	7%	6%	7%	0%	3%	50%
		S2	-12%	-12%	-11%	-13%	-11%	0%	-15%	7%
	1	Baseline	429	13,123	2,377	195	117	1,650	25.1	537
		S1	18%	19%	15%	16%	15%	0%	28%	31%
		S2	-13%	-12%	-13%	-14%	-13%	0%	-6%	6%
	2	Baseline	383	11,987	2,175	179	106	1,320	22.2	84
		S1	2%	1%	1%	0%	1%	0%	2%	120%
		S2	-17%	-18%	-16%	-19%	-17%	0%	-21%	16%
	3	Baseline	307	9,589	1,726	138	85	1,291	25.4	102
		S1	14%	16%	14%	15%	14%	0%	-12%	57%
		S2	-2%	-1%	-1%	-1%	-2%	0%	-23%	27%
	4	Baseline	449	14,095	2,564	204	125	1,249	27.2	31
		S1	-9%	-8%	-10%	-10%	-10%	0%	1%	409%
		S2	-24%	-23%	-22%	-25%	-22%	0%	-17%	64%
Evening peak	OC	Baseline	1,778	54,819	9,847	794	501	2,223	61.8	692
		S1	2%	3%	3%	2%	2%	0%	-1%	54%
		S2	-13%	-12%	-10%	-12%	-12%	0%	-16%	13%
	1	Baseline	498	14,821	2,593	235	148	1,687	23.4	382
		S1	6%	9%	5%	6%	4%	0%	24%	35%
		S2	-7%	-5%	-6%	-7%	-7%	0%	-3%	16%
	2	Baseline	410	12,052	2,281	197	127	1,443	22.4	107
		S1	-5%	-5%	-2%	-5%	-4%	0%	-6%	75%
		S2	-18%	-18%	-15%	-19%	-16%	0%	-23%	7%
	3	Baseline	368	11,090	1,963	178	106	1,382	26.1	109
		S1	2%	4%	5%	4%	3%	0%	-14%	62%
		S2	-11%	-10%	-7%	-9%	-10%	0%	-27%	24%
	4	Baseline	432	12,664	2,291	202	131	1,348	27.3	27
		S1	-14%	-13%	-12%	-13%	-14%	0%	-4%	294%
		S2	-25%	-25%	-22%	-24%	-24%	0%	-19%	49%
Two time periods	OC	Baseline	3,426	106,152	19,164	1,550	956	4,391	60.2	1543
		S1	5%	5%	5%	4%	4%	0%	1%	52%
		S2	-12%	-12%	-11%	-13%	-12%	0%	-16%	10%
	1	Baseline	927	27,944	4,970	430	265	3,337	24.3	919
		S1	17%	19%	15%	16%	15%	0%	-2%	95%
		S2	-10%	-8%	-10%	-11%	-12%	0%	-22%	11%
	2	Baseline	793	24,039	4,456	376	233	2,763	22.3	919
		S1	-1%	-2%	-1%	-3%	-1%	0%	-13%	60%
		S2	-17%	-18%	-16%	-19%	-17%	0%	-25%	25%
	3	Baseline	675	20,679	3,689	316	191	2,673	25.8	211
		S1	8%	10%	10%	9%	8%	0%	-2%	355%
		S2	7%	-5%	-4%	-5%	-6%	0%	-18%	57%
	4	Baseline	881	26,759	4,855	406	256	2,597	27.3	58
		S1	-11%	-11%	-11%	-11%	-11%	0%	-1%	54%
		S2	-24%	-23%	-23%	-24%	-24%	0%	-16%	13%

Notes: *veh: vehicle; OC: Overall Corridor; 1: Intersection 1 (RBT1/I1area); 2: Intersection 2 (RBT2/I2area); 3: Intersection 3 (RBT3/I3area); 4: Intersection 4 (RBT4/I4area);*

Shaded area indicates maximum reduction recorded.

4.3.3. Spatial distribution of emissions

To complete the analysis, speeds and CO_2 emission distributions in each 10-m segment length were compared along the corridor, considering all intersections, which consisted of roundabouts (Baseline), traffic lights (S1), and stop-controlled (S2) (**Figure 4.5**). The comparison was conducted for through movements (north-south and south-north) and time periods. The analysis indicated that the spatial distributions of speed and CO_2 were highly symmetrical along the selected corridor for all roundabouts. The spacing between adjacent roundabouts and the geometric features were similar for all roundabout layouts. Higher deceleration and acceleration rates were recorded upstream and downstream of the intersections in both directions. Accordingly, sharper variation of the CO_2 curve between the exit and the yield or stop lanes was observed (the overall contribution on emissions was approximately 35%, 30% and 34% on Baseline, S1, and S2, respectively). When vehicles travelled toward adjacent intersections, they generated higher CO_2 levels after traffic light implementation (more than 15%).

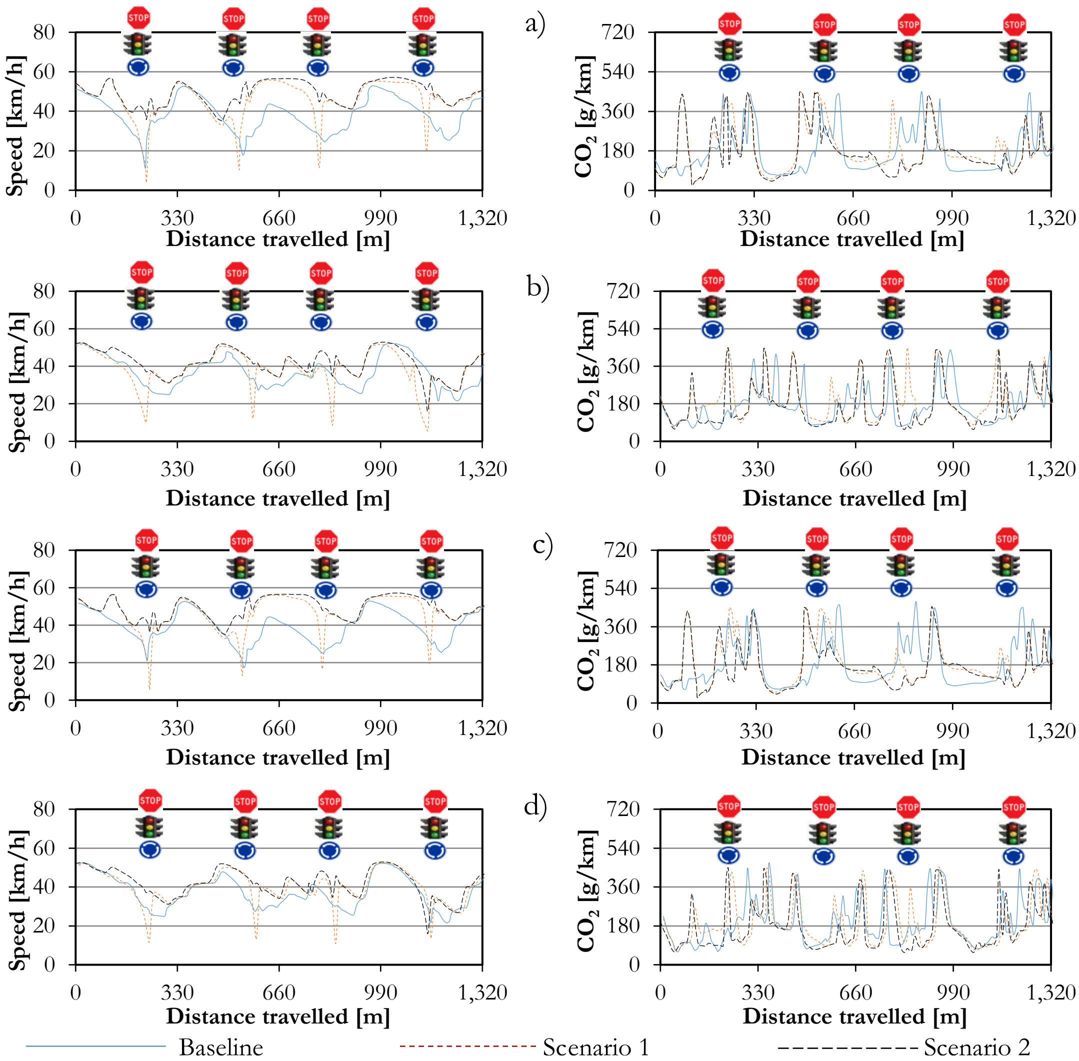


Figure 4.5 Speeds and CO_2 distributions along the corridor per scenario: a) Morning peak (north-south); b) Morning peak (south-north); c) Evening peak (north-south); and d) Evening peak (south-north).

4.4. Conclusions

This study explored the effect of an urban corridor with four roundabouts on traffic performance and emissions generated from vehicles. A microscopic traffic model was integrated in conjunction with emissions models to assess the consequences of replacing a series of roundabouts in arterials (Baseline) by traffic lights (Scenario 1) and stop-controlled intersections (Scenario 2). The traffic performance and emissions of each solution were compared at the arterial-level, intersection-level, and morning and evening peak periods.

The following main findings were found at a corridor level:

- Roundabouts led to the lowest number of vehicle stops and were environmentally better than the traffic lights solution (4% to 5%, depending on the pollutant);
- Traffic lights were the worst solution for both time periods: emissions increased about 7% and 2% compared with roundabout layout in the morning and evening peak periods, respectively; the number of stops increased more than 50%;
- Stop-controlled was the best solution in both time periods for emissions and some mobility measures: 12% less vehicle emissions and nearly 16% less travel time.

The following findings were obtained at the intersection level:

- Roundabouts recorded the lowest number of vehicle stops and fewer total emissions than traffic lights solution (8% to 19%, depending on the pollutant) at four-leg intersections;
- For traffic lights, the average total emissions decreased in the evening peak period (2% to 14%, depending on the pollutant) at three-leg intersections, and there was approximately 2% less travel time at three-leg intersections;
- Stop-controlled led to a decrease in the average total emissions compared with the roundabout solution (3% to 24%, depending on the intersection), and travel time was shortened by 6% to 23% (depending on the intersection).

The unbalanced traffic flows between main roads (> 500 vph) and minor roads (< 125 vph in most approaches) justified the advantages of the implementation of the stop-controlled solution in the case study.

The findings of the study confirmed that the vehicles that travelled along the mid-block areas toward adjacent traffic lights drove at higher speeds compared with adjacent roundabouts, and consequently higher emissions were produced throughout the corridor.

This research highlights the importance of identifying the specific characteristics of a corridor before implementing a specific type of intersection to enhance traffic performance and emissions impacts. Moreover, the study determines whether there is a need for a corridor-level analysis, an intersection-level analysis, or both.

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5. TURBO-ROUNDABOUTS IN CORRIDORS

This chapter extends the objectives posed in Chapters 3 (hotspot emission locations on a corridor level) and 4 (comparing corridors with different forms of intersections) in real-world turbo-roundabout corridors. Thus, the location and quantification of highest emissions segments in 3 corridors with different turbo-roundabout layouts is examined. The comparison between turbo-roundabout and conventional two-lane roundabout corridors as a traffic performance and emissions perspectives is also conducted.

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Abstract

The number of turbo-roundabouts constructed in Europe has grown steadily in the past decade. While there has been extensive work on the operational and environmental impacts of isolated turbo-roundabouts, research on closely-spaced turbo-roundabouts along corridors is somewhat lacking.

The objective of this research is to evaluate the impact of turbo-roundabout corridors on both traffic performance and emissions. The research has three major thrusts: 1) to identify the hotspot emission locations along turbo-roundabout corridors; 2) to compare the overall performance of turbo-roundabout corridors against conventional two-lane roundabouts on arterials; 3) to address the integrated effect of geometric and operational characteristics of turbo-roundabout corridors on carbon dioxide, carbon monoxide, nitrogen oxides and hydrocarbons emissions.

Vehicle activity along with traffic flow data were collected from three turbo-roundabout corridors in the Netherlands. Site-specific operations were analyzed using microscopic traffic and emissions platforms (respectively, VISSIM and Vehicle Specific Power – VSP).

The results showed that emission hotspots along these corridors occurred in the segments located just downstream of the turbo-roundabout, both in absolute terms (more than 30% of total emissions) and per unit distance. It was also found that the implementation of two-lane roundabout corridors outperformed the turbo-roundabout corridors in terms of vehicle emissions, however the differences were not statistically significant (p-value $<$ 0.05). Data analysis indicated that an additional decrease in corridor's emissions (4-11%, depending on the pollutant) may be reached by altering the spacing (from 180 to 240 m) between two-closely spaced turbo-roundabouts.

Keywords: Emissions, Spacing, Traffic performance, Turbo-roundabout corridors.

5.1. Introduction and Research Objectives

Turbo-roundabouts implementation as a traffic control at intersections has been progressively increasing in the past decade. This layout represents an innovative arrangement of conventional multi-lane roundabout that has altered intersection design in some European countries (1).

Turbo-roundabouts were first developed as a means to deal with some operational issues concerning two-lane roundabouts, namely the occurrence of unwanted weaving movements due to lane changing between outer and inner circulating lanes in this layout. An important benefit of turbo-roundabouts is therefore a reduction in the number of conflict points due to continuous spiral circuits, physically delineated by raised curbs at the entry, circulating and exit areas (2).

Figure 5.1 depicts a conventional four-leg two-lane roundabout and a basic turbo-roundabout of similar size.

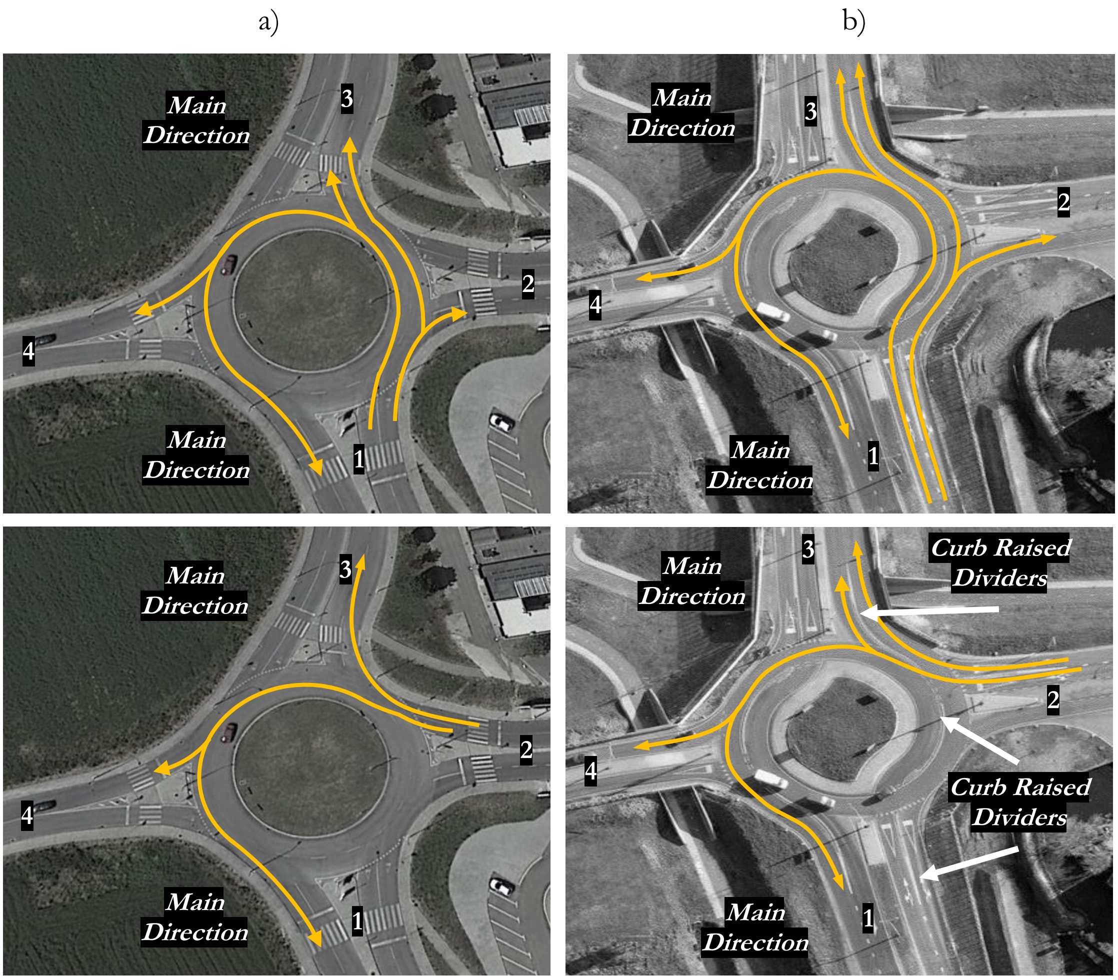


Figure 5.1 Differences between roundabout layouts: a) Conventional Two-lane roundabout; b) Basic Turbo-roundabout (3) [Source https://www.google.pt/maps].

The main differences between layouts are as follow (2):

- On a conventional roundabout, the outer circulatory lane at the major entrances (1 and 3) is used by a fraction of the through movements; on a turbo-roundabout, the opposing traffic is concentrated in a single-lane;
- On a conventional roundabout, drivers in the right lane of the minor entrances (2 and 4) are affected by all circulating vehicles; on a turbo-roundabout, the outer entry lane is used only for right-turning (2-3 and 4-1 movements), and the opposing traffic is reduced since a proportion of the through traffic is physically separated at the exit;
- On a conventional roundabout, right-turning traffic must use the right entry lane (2-3 and 4-1 movements); on a turbo-roundabout, drivers at the minor entrances can use both the left and right entry lanes.

There is significant literature on the operational (4-11) and environmental (3, 12) evaluation of isolated turbo-roundabouts. However, research on the performance of series of interdependent turbo-roundabouts along an arterial is scarce. Basically, the notion of moving platoons of vehicles to maximize the performance efficiency is not applicable to roundabouts or turbo-roundabouts because gap acceptance principles allow more dispersed flows (13).

There are several unanswered questions about the operational characteristics and environmental benefits of turbo-roundabout corridors. If vehicles at a downstream turbo-roundabout are mostly turning left, and simultaneously the mid-block of an upstream turbo-roundabout is congested, corridor's performance may be considerably worse than an equivalent two-lane roundabout corridor. This is because drivers at a turbo-roundabout have less flexibility to select the entry lane, which allows a smaller range of traffic splits before congestion occurs. Additionally, the impacts on queues and emissions may be more sensitive for very short spacing between adjacent turbo-roundabouts, and could suggest a different traffic control for a given intersection along the corridor.

The objective for this study is to quantify and contrast traffic performance and emissions in the context of turbo-roundabout corridors. The overall performance of corridor with turbo-roundabouts is hypothesized to be inferior to that of an equivalent conventional two-lane roundabout corridor. This research investigates the above concerns at real-world turbo-roundabout corridors that experience variations in traffic flow and directional splits at each entry. The study also includes a performance assessment of closely-spaced turbo-roundabouts.

In summary, the major components of the research include:

- Identifying hotspot emission locations at turbo-roundabout corridors with variations in spacing, traffic flow and directional splits distributions;
- Assessing the collected field data and comparing the performance of turbo-roundabout corridors relative to equivalent two-lane roundabout corridors;
- Improving the corridor environmental performance by proposing changes to some operational and geometric variables.

5.2. Literature Review

The capacity, safety and emissions at isolated turbo-roundabouts is well researched, and methods to compare their performance with conventional roundabouts are well established. Safety benefits of turbo-roundabouts are recognized in most previous works (2, 11, 12, 14), however, the literature review indicates a dearth of knowledge about the capacity and environmental benefits of turbo-roundabouts while operating in corridors.

Early studies carried out on turbo-roundabout capacity have shown an increased capacity compared with that of conventional roundabouts of similar size (4-6). Nevertheless, site-traffic conditions and geometric layouts tend to influence the overall performance of turbo-roundabouts (7, 11). Corriere and Guerrieri (8) explain that each approach capacity at turbo-roundabouts depends on lane capacity, conflicting traffic flows, pedestrian activity, driving habits and the balance of traffic demand on each approach. Vasconcelos et al. (12) stated that turbo-roundabout can only reach comparable capacity levels to the traditional two-lane layout when the proportion of right-turning traffic is unusually high (>60%). On the other hand, Lambertus et al. (9) highlighted the fact that compact German two-lane roundabouts yielded lower capacity levels than Dutch turbo-roundabouts because of better use of inner circulating lane in the latter layout.

In a recent study on emissions at roundabouts by Vasconcelos et al. (12), turbo-roundabout was found to be deficient in reducing carbon dioxide (CO_2) and nitrogen oxides (NO_X) emissions when compared with a two-lane roundabout, although it reduced other local pollutants (carbon monoxide - CO and hydrocarbons - HC). Fernandes et al. (3) confirmed that vehicles driving through turbo-roundabouts generated more emissions (15-22%, depending on the pollutant) compared with multi-lane roundabouts.

Some local authorities in the United States (US) have recently proposed and constructed several conventional roundabout corridors (13). In this context, interest also is growing about the turbo-roundabout concept in the US (15), but little research has been conducted to determine objectively the efficacy of series of turbo-roundabouts on an arterial as compared to conventional multi-lane layouts.

Silva et al. (16) compared traffic performance, fuel use, and pollutant emissions at turbo and two-lane roundabouts corridors. The site included three intersections spaced approximately 435 m and a total length of 1,800 m. They found that the turbo-roundabout corridor was ineffective after reaching saturation, especially in terms of traffic performance. However, the aforementioned research had three limitations: *1*) the corridor did not include closely-spaced intersections; *2*) vehicle dynamic data were only collected from conventional roundabouts (16); and *3*) only one site was evaluated, which does not allow transferability of the findings to other corridors.

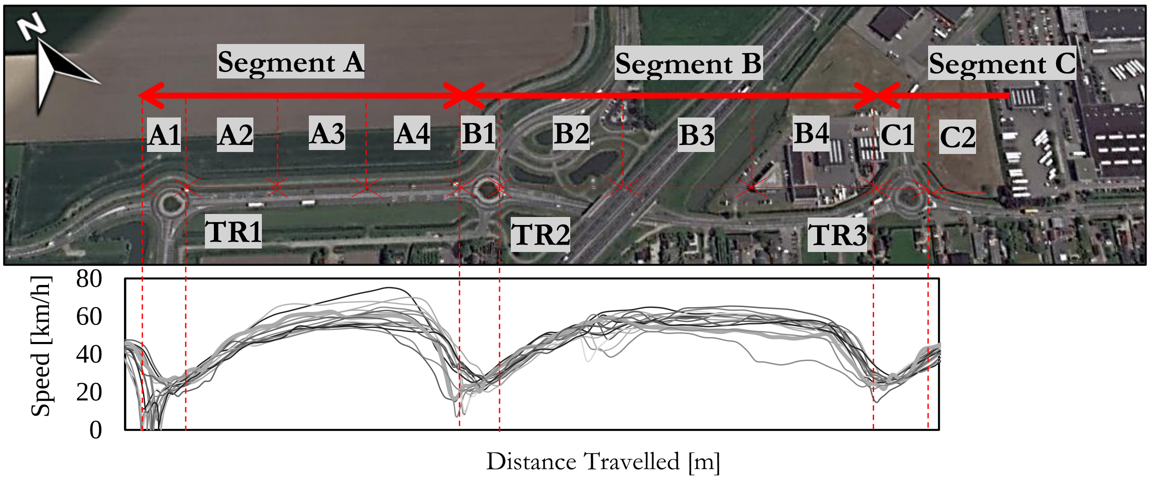
From the facts presented above, two main research gaps are revealed: *1*) none of previous studies assessed the situations of overlapping influence areas between adjacent turbo-roundabouts or short upstream-downstream segments at either end of the turbo-roundabout; and *2*) little attention was given to the impact of the geometric characteristics of turbo-roundabout corridor on measured or estimated vehicle emissions.

5.3. Methodology

The methodology involved a combination of empirical data analysis and microsimulation. First, the analyst collected vehicle dynamics data (second-by-second speed and acceleration-deceleration), and measurements of overall congestion levels at several turbo-roundabout corridors. Each corridor was then sub-divided into several sub-segments. The Vehicle Specific Power (VSP) methodology (17) was used to estimate CO_2, CO, NO_X and HC emissions, with the intent to identify the hotspot emission locations. Subsequent to the field work, each corridor was coded in the VISSIM traffic model (18), and then calibrated according to the site-specific characteristics. Vehicle Specific Power (VSP) (17) and EMEP/EEA (19) methodologies were paired with VISSIM to compare emissions, energy and traffic performance measures between these corridors and equivalent two-lane roundabout corridors.

5.3.1. Segments and sub-segments definitions

The analysis corridor was divided into different sub-segments to quantify emissions impacts. This level of segmentation is based on changes in speeds as drivers decelerate while approaching the turbo-roundabout, negotiate the corresponding circulating lane and accelerate while leaving the turbo-roundabout back to cruise speed. The research team defined a segment from the downstream exit lane from one turbo-roundabout to the upstream yield lane of the next roundabout in the direction of travelling. **Figure 5.2** shows the suggested segmentation along a corridor with two pairs of turbo-roundabouts TR1/TR2 and TR2/TR3, separated by Segments A and B, respectively.



Legend: A1: Circulating Area of segment A; **A2**: Downstream of segment A; **A3**: Midblock of segment A; **A4**: Upstream of segment A; **B1**: Circulating Area of segment B; **B2**: Downstream of segment B; **B3**: Midblock of segment B; **B4**: Upstream of segment B; **C1**: Circulating Area of segment C: **C2**: Downstream of segment C

Figure 5.2 Segments and sub-segments definition for a corridor with turbo-roundabouts [Source https://www.google.pt/maps].

Based on vehicle activity data, each segment is comprised by different sub-segments:

- Circulating Area: Vehicle decelerates to negotiate traffic in the circulating area of turbo-roundabout and then accelerates while exiting the turbo-roundabout (deceleration followed by an acceleration pattern);
- Downstream: Vehicle accelerates after exiting the turbo-roundabout back to cruise speed (acceleration only);
- Mid-block: Vehicle operates near the cruise speed with slight acceleration or deceleration rates (constant speed);
- Upstream: Vehicle begins to decelerate while approaching the downstream turbo-roundabout (deceleration only).

An influence area must be defined to estimate the length of roadway upstream and downstream of a turbo-roundabout over which speeds are reduced due to the presence of the turbo-roundabout (13). To be consistent with the Highway Capacity Manual procedure (20), the downstream, midblock and upstream sub-segments are assumed to be equal in length.

5.3.2. Study sites identification

To account for applicability and variability in real-world turbo-roundabout layouts, three corridors in the Netherlands (N1, N2, and N3) were selected. The dataset includes 10 turbo-roundabouts, and 20 downstream and upstream sub-segments (considering both directions of travel). The candidate sites have a similar overall corridor length but vary in spacing between roundabouts (ranging from 180 m to 650 m) with approach speed limits mostly below 45 km/h.

The first site (N1) is near a commercial area and is located 10 km southeast of Gouda. Approximately 7% of N1 traffic is composed of Heavy-Duty Vehicles (HDV) and about 30% of movements at TR2 (southeast-northwest) and TR3 (southeast-northwest) are left-turning.

The second site (N2) is near an urban area and includes a turbo-roundabout interchanges (TR3). This corridor primarily serves through traffic (eastbound and westbound).

Finally, N3 site has two-bridge turbo-roundabout interchanges (TR3 and TR4) and is near the urban area of Leiden. Some entries of TR2 and TR3 along N3 have moderate percentage of right-turning. N3 also has one pair of turbo-roundabouts (TR1/TR2) located in close proximity to each other (~180 m), and therefore make the case for overlapping turbo-roundabouts influence areas.

Table 5.1 summarizes the relevant information of each site including layout, GPS coordinates, traffic flows, spacing between adjacent turbo-roundabouts (measured from the downstream exit lane from one turbo-roundabout to the upstream yield lane of the adjacent turbo-roundabout in the direction of travel) and length of corridor.

Table 5.1 Summary of Study Site Characteristics

Site ID	Turbo RBT ID	Layout (21)	GPS Coordinates	Traffic [vph]		Distance from upstream roundabout [m]	Average Spacing [m]	Length of the corridor [m]
				Arterial[a]	Side Legs			
N1	TR1	Knee	52° 1'23.05"N 4°36'42.79"E				375 (0.28)[b]	1,300
	TR2	Egg	52° 1'15.12"N 4°36'55.95"E	540	300	300		
	TR3	Partial	52° 1'3.83"N 4°37'12.55"E	635	450	450		
N2	TR1	Partial	51°59'13.56"N 4°29'2.26"E				473 (0.53)[b]	1,400
	TR2	Egg	51°58'59.42"N 4°29'30.32"E	595	650	650		
	TR3	Basic	51°58'51.25"N 4°29'42.79"E	650	295	295		
N3	TR1	Basic	52° 9'40.38"N 4°32'57.47"E				260 (0.26)[b]	1,400
	TR2	Basic	52° 9'45.85"N 4°33'4.83"E	360	180	180		
	TR3	Egg	52° 9'51.37"N 4°33'24.42"E	470	340	340		
	TR4	Partial	52° 9'43.99"N 4°33'38.42"E	365	260	260		

Note: *a) From data provided by Dutch authorities (values by road lane);*
b) Coefficient of Variation (Standard Deviation of Spacing/Average Spacing).

Legend: *Knee turbo-roundabout: has right-turn bypass lanes in one or more entries;*
Egg turbo-roundabout: the number of lanes in the side legs differs from that on the turbo-roundabout itself (typically these legs are single-lane);
Partial turbo-roundabouts: has one lane for through traffic at least in one of the movements.

5.3.3. Field Data Collection

In this section, the main steps of the monitoring plan are enumerated. Before proceeding with the data collection, the authors identified the relevant data for assessing corridor's performance. The types of data of interest are:

Site-specific data

- Posted speed limit;
- Turbo-roundabout geometry and spacing.

Time dependent flow data

- Entry and circulating traffic flows;
- Directional split of traffic;
- Vehicle dynamic data (speed and acceleration-deceleration on a second-by-second basis).

The research team scouted and collected these data at the selected study cases during the afternoon period (4-6 p.m.) on three typical weekdays (Tuesday to Thursday). Traffic volumes were gathered from one overhead video and a smartphone in 5-min time intervals. Equipped light duty vehicle performed several trips at the corridor level (mainly through movements).

A GPS data logger and an Onboard Diagnostic Reader (OBD) sensor were installed in a test-vehicle to record vehicle speed, distance travelled, and deceleration-acceleration rates in 1-second interval. A male driver of age 30 with more than 10 years of driving performed several runs during off-peak, morning, and evening periods (from 8 a.m. to 6 p.m.) in May 2016. These runs were conducted with different driving types (calm, intermediate and aggressive) to take into account different traffic conditions.

The sample size (number of runs) for vehicle dynamic data collection and videotaping was evaluated using the Modified Method proposed by Li et al. (22). Thus, total data collected included 315 GPS travel runs (≈105 per site), which corresponded to a road coverage of 500 km, and 4 h of video data at each location (48 data samples of 15 min).

5.3.4. Emissions Estimation

Frey et al. (17) introduced a "modal binning approach" for calculating vehicular emissions based on the Vehicle Specific Power (VSP). VSP takes into account engine power demand associated with changes in vehicle potential and kinetic energies, aerodynamic drag, and rolling resistance (17, 23).

VSP values are categorized into 14 modes, and an emission factor for each mode is used to estimate the footprints of CO_2, CO, NO_X and HC emissions for different vehicles types such as Gasoline Passenger Vehicles (GPV) (24), Diesel Passenger Vehicles (DPV) (25), Light Duty Diesel Trucks (LDDT) (25), and Hybrid Electric Vehicles (HEV) (26). These values are the average of tailpipe emissions measured by Portable Emissions Measurement Systems (PEMS) (17).

This research initially focused on emissions along individual sub-segments of turbo-roundabout corridors based on field data. Thus, CO_2, CO, NO_X, and HC modal rates were weighted by the amount of time spent in each VSP mode for a given speed profile.

5.3.5. Microsimulation platform for traffic and emissions

5.3.5.1. Traffic and emissions modelling

The microscopic traffic model VISSIM 5.3 was used to simulate traffic operations (18). All simulation experiments were made for the analysis period between 4:30 p.m. and 6:00 p.m. with a 30-min "warm-up" period prior to 5:00 p.m. to load the study domain adequately with corresponding traffic flow.

Network links coding was made following good practices for roundabouts (27) in which the number of links to represent the intersection was equal to the number of entry and exit legs, and considering the contribution of each entering, circulating and exiting lanes. Several links were coded in the turbo-roundabout influence areas to fulfill reproduce speed profiles as vehicles driving though turbo-roundabouts. Lastly, traffic flows were assigned for each link and according the intersection-specific split distributions, and then GPS traces were matched to each coded link.

Emissions estimates using VSP methodology were based on vehicle dynamics data (speed and acceleration-deceleration) gathered from the VISSIM traffic model calibrated with GPS and

OBD data (**Section 5.3.5.2**). A console application in C# programming language was developed to compute second-by-second vehicle dynamics data from VISSIM output. The research team fit as much as possible the emission rates to the Dutch fleet, namely engine capacity, average fleet age and fuel type (12, 25). For all sites, the following fleet composition was used (28, 29): 70% of GPV, 15% of DPV, 6% of HEV and 9% of LDDT.

Additionally, the EMEP/EEA method was used to estimate HDV emissions (19) at site N1. Emission factors for diesel heavy-duty vehicles from Euro I to Euro VI emission standards are calculated as a function of the average speed. The generic functions and the values for the coefficients for these equations can be found elsewhere (19). The emissions' factors depend on the engine capacity and age of each vehicle class and fuel type. For other sites, HDV were excluded from the analysis since they represented less than 2% of the traffic composition.

5.3.5.2. Traffic Model Calibration and Validation

The traffic model was calibrated and validated using the empirical data collected from turbo-roundabout corridors during evening peak period (from 4 p.m. to 6 p.m.). The procedure was conducted separately by site and using different data sets for calibration (≈80%) and validation (≈20%).

VISSIM model was first calibrated by modifying driver behavior and vehicle performance parameters, and by assessing their impact on traffic flows and speeds by coded link. The following parameters were calibrated: car-following, lane-change, gap acceptance parameters, and simulation resolution (18). For each site, the calibration proceeded in three steps:

1st) Using default values of car-following, lane-change, gap acceptance parameters, and simulation resolution, the observed and simulated traffic flow and speeds were compared;

2nd) These parameters were optimized by using Simultaneous Perturbation Stochastic Approximation (SPSA) algorithm (30) in which the objective function was the minimization of Normalized Root Mean Square (NRMS);

3rd) The optimization was stopped after complying the following calibration target – at least 85% of all links must meet the criteria of GEH (acronym for Geoffrey E. Havers) < 4 (31).

The model validation addressed how well the simulated travel time and accelerations matched the field data. Observed and simulated accelerations were computed by coded link.

5.3.5.3. Simulated Scenarios

The baseline scenario represents well-calibrated turbo-roundabout corridors with the observed traffic flows at N1, N2 and N3 that had been used to calibrate the traffic model. After that, curb raised dividers are removed, and inner circle of each one of the turbo-roundabouts is reshaped to the final conventional two-lane layout according to Dutch design (32). The number of approach lanes on the major and minor roads was assumed the same as in the baseline scenario.

5.4. Results and Discussion

In this section, the main results from the empirical data (**Section 5.4.1**) are analyzed followed by the simulation calibration and validation, and experiments (**Section 5.4.2**).

5.4.1. Segments emissions

This section uses the collected data to estimate vehicular emissions at each specified segment using VSP methodology. Emissions per vehicle and per kilometer by segment are presented in **Table 5.2**. The results indicate that:

- The highest amounts of CO_2, CO, NO_X and HC emissions per vehicle (nearly 35%, 38%, 40% and 33%, respectively) in N1 corridor were recorded downstream. This segment corresponds to about 25% of travel distance across the corridor. In contrast, circulating areas had a moderate impact on emissions (overall contribution on total emissions was less than 22%). This was mostly due to low speeds and smooth acceleration-deceleration rates at the circulatory ring of turbo-roundabouts;
- Downstream segments generated the highest amount of emissions per kilometer travelled across N1. For example, NO_X emissions per unit distance were 69% higher than the average values for the entire corridor. Circulating areas also reached emissions per kilometer higher than average N1 values, especially for CO_2 (20% higher than the average CO_2 value);
- The results from N2 corridor showed an identical trend. Downstream segments accounted for 41% of CO_2 emissions, while covering 28% of travel distance. Because turbo-roundabouts are generously spaced, vehicles attained cruise speeds at midblock. Specifically, these sub-segments contributed to more than 26% of total emissions;
- Emissions per unit distance along the downstream sub-segments (ranged from 19% to 63% for HC and NO_X) and circulating areas (ranged from 14% to 30% for NO_X and HC) were higher than the average N2 corridor value. Interestingly, emissions per kilometer at the mid-block were lower than the average corridor value (~23%). This is explained by the presence of smooth speed profiles;
- Downstream segments had a major impact on emissions across the N3 site. Vehicles emitted about 34% and 35% of CO_2 and CO emissions, respectively, in 23% of travel distance. Similarly, circulating areas and mid-block segments also had a major impact on emissions (~26% of total emissions);
- Hotspot emission locations (by unit distance) at the N3 site were found at downstream segments. This was particularly true for NO_X emissions (48% higher than the average corridor value).

Table 5.2 Emissions per vehicle and per kilometer by segment across turbo-roundabout corridor

Site	Pollutant	CA	D	M	U	Total	Pollutant	CA	D	M	U	Average
N1	CO_2 [g]	32	53	41	25	**151**	CO_2 [g/km]	207	245	147	93	**173**
	CO [mg]	56	113	79	48	**296**	CO [mg/km]	362	542	284	168	**339**
	NO_X [mg]	40	87	61	29	**217**	NO_X [mg/km]	256	419	220	101	**249**
	HC [mg]	1.8	2.7	1.8	1.8	**8.1**	HC [mg/km]	11.8	11.7	7.2	6.3	**9.2**
N2	CO_2 [g]	27	66	43	25	**161**	CO_2 [g/km]	194	219	120	89	**155**
	CO [mg]	47	123	76	45	**291**	CO [mg/km]	339	407	212	158	**279**
	NO_X [mg]	33	102	57	27	**219**	NO_X [mg/km]	235	336	159	95	**206**
	HC [mg]	1.8	2.7	1.8	1.8	**8.1**	HC [mg/km]	10.8	9.9	6.3	6.3	**8.3**
N3	CO_2 [g]	53	63	51	20	**187**	CO_2 [g/km]	204	222	165	78	**167**
	CO [mg]	99	123	91	35	**347**	CO [mg/km]	369	433	282	142	**304**
	NO_X [mg]	80	95	68	19	**262**	NO_X [mg/km]	284	342	223	77	**232**
	HC [mg]	2.7	2.7	1.8	1.8	**9.0**	HC [mg/km]	10.8	9.9	7.2	6.3	**8.6**

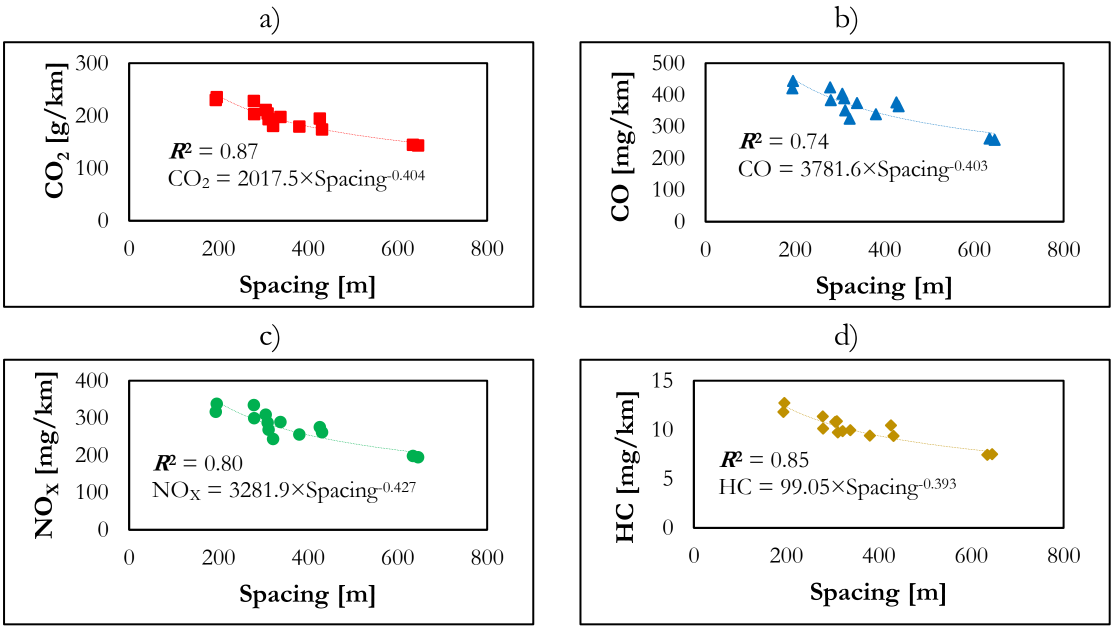
Legend: *CA: Circulating Area – A1 + A2 + A3 + A4 (If exists in the corridor);*
D: Downstream – B1 + B2 + B3 + B4(if exists in the corridor);
M: Midblock – M1 + M2 + M3 + M4(if exists in the corridor);
U: Upstream – U1+ U2 + U3 + U4(if exists along corridor);
Shadow cells indicate the highest value

It must be emphasized that the impact of downstream might be also observed in other traffic control treatments such as signalized or stop-controlled intersections. However, this phenomenon only occurs when vehicles makes a complete stop at the intersection. On a circular intersection, the acceleration episodes always occur even though vehicles do not make a stop on the approach.

In summary, vehicles at the downstream sub-segments generated the highest emissions levels both in absolute terms and per kilometer. Significant emissions (by unit distance) were also observed in circulating areas at the N3 site (23% higher than the average corridor value) where average spacing was the lowest among corridors (see **Table 5.1** for those details). This suggests that the spacing may influence acceleration-deceleration profiles, and therefore the spatial distribution of emissions.

Thus, the spacing values (considering both directions of travel) were plotted against the global and local pollutant emissions per kilometer by segment. The estimated regression models (using power functions) confirmed the prior premises, as shown in **Figure 5.3**. For these models, the analysis of R^2 (F-test) and the analysis of coefficients for the model (T-test) resulted in p-values lower than 0.001. The statistical correlations between spacing and CO_2, CO, NO_X and HC were R^2 = 0.87, 0.74, 0.80 and 0.85, respectively.

The scattered graphs showed that for low spacing values (<200 m), the emissions were approximately 30% higher than those observed for moderate spacing values (~350 m). These findings are in line with previous research conducted in conventional single-lane and multi-lane roundabouts corridors in the US (33).



Note: *Analysis of* R^2 *(F-test) and model coefficients (T-test) resulted in p-values below 0.001 for all pollutants.*

Figure 5.3 Emissions per kilometer versus spacing: a) CO_2; b) CO; c) NO_X; d) HC.

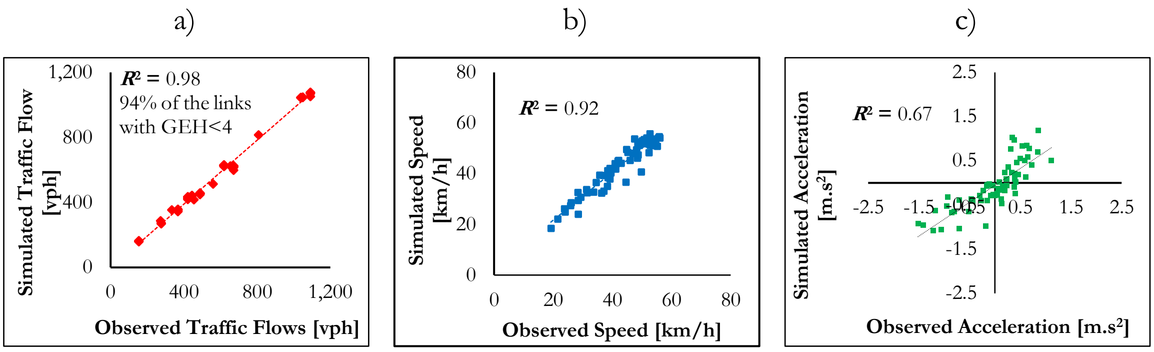
5.4.2. Simulation Model Experiments and Results

5.4.2.1. Model Calibration and Validation

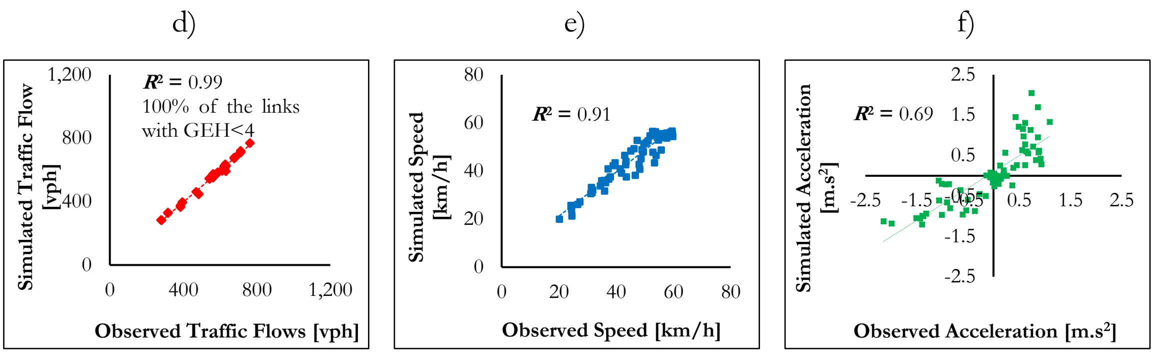
Summary statistics of the VISSIM calibrated model parameters at the candidate sites are exhibited in **Figure 5.4**. The graphs also include the corresponding values for car following and gap acceptance parameters. The variation in lane change parameters did not affect NRSM and GEH values. This is mostly corridors operate above capacity and therefore vehicles with a predefined route choice are not retained before curb raised dividers at the turbo-roundabouts approaches. The existing two-lane segments also have short lengths that allow few overtaking maneuvers. A simulation resolution of 10 time steps per simulation seconds was used in all sites to fit the time resolution of traffic and emissions models (a second-by-second basis).

The results demonstrated a very good fit between simulated and observed data using a linear regression analysis. The predicted R^2 were higher than 0.90 for simulated traffic flows (**Figure 5.4** a, d, g) and speeds (**Figure 5.4** b, e, h) using site-calibrated values. In turn, more than 90% of the coded links (between 62 and 73 links, depending on the site) yielded a GEH value lower than 4, thereby satisfying the calibration criteria (31).

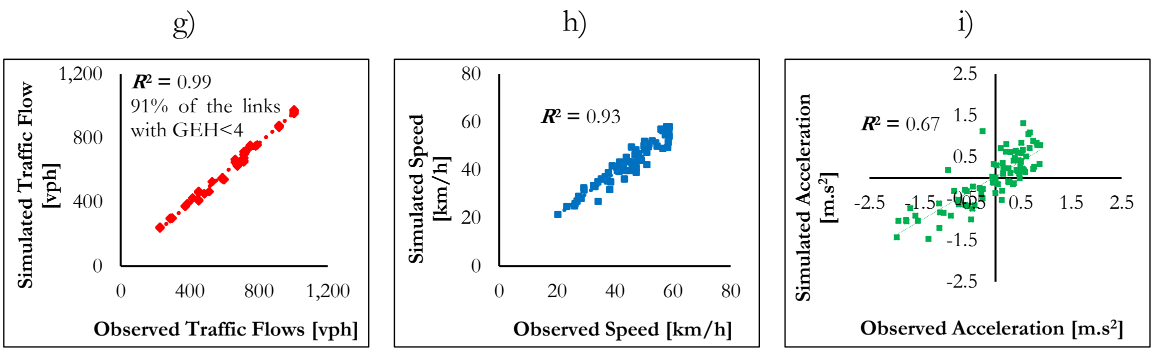
For validation, the comparison of observed and simulated travel time was conducted using a different data set from the calibration and additional 15 random seed runs, as suggested elsewhere (34). SPSS software was used to perform the statistical analysis. The maximum average percent travel time differences [using 30 floating car runs (31) by through movement] were observed in the N1 site on the southeast-northwest direction (~6%). This is explained by the high traffic demand on that site that led to travel time variability. However, the difference between observed and simulated travel time was not statistically significant (p-value > 0.05) on all routes. The corresponding acceleration and deceleration values (**Figure 5.4** c, f, i) also confirmed a good correspondence of the modeling platform. Using the calibrated VISSIM parameters, linear trend lines matched the acceleration data with correlation coefficients ranged from 0.67 to 0.69 for N1 and N3 sites.



Car following – Average standstill distance (m): 0.85 Additive safety distance: 0.8 Multiple part of safety distance: 0.9
Gap acceptance – Front Gap: 0.25 s; Rear Gap: 0.25 s; Safety Distance Factor: 1.0



Car following – Average standstill distance (m): 0.9 Additive safety distance: 1.0 Multiple part of safety distance: 1.0
Gap acceptance – Front Gap: 0.3 s; Rear Gap: 0.3 s; Safety Distance Factor: 1.0



Car following – Average standstill distance (m): 0.85 Additive safety distance: 0.9 Multiple part of safety distance: 0.9
Gap acceptance – Front Gap: 0.3 s; Rear Gap: 0.3 s; Safety Distance Factor: 1.0

Figure 5.4 Observed versus Simulated parameters using calibrated model: a) N1-Volumes; b) N1-Speed; c) N1- Acceleration-Deceleration; d) N2-Volumes; e) N2-Speed; f) N2-Acceleration-Deceleration; g) N3-Volumes; h) N3- Speed; i) N3- Acceleration-Deceleration.

5.4.2.2. Comparing Turbo and Conventional Roundabout Emissions and Traffic Performance

This section compares the VISSIM simulated vehicular emissions and traffic performance measures of turbo-roundabout corridors and proposed conventional two-lane roundabout corridors.

When N1 corridor is considered, no differences between two-lane and turbo-roundabout corridors were observed (**Table 5.3**). The corridor with conventional roundabouts had average emissions reductions of about 1%, and approximately 2% lower travel time. However, turbo-roundabout corridor yielded fewer stop-and-go situations (~4%) when compared to the two-lane layout. This is mostly explained by the fact that vehicles in the right entry lane of TR2 on the minor entries are affected by the fraction of the opposing traffic since two circulating lanes are available for through traffic. Yet vehicles spent more time driving along turbo-roundabout corridor compared to two-lane layout (caused by slow approach and circulating speeds as a result of using curb raised dividers at the turbo-roundabouts).

The differences in both layouts at the N2 site were more pronounced than in the N1 case. Corridor with two-lane roundabouts yielded the highest emissions reductions in CO_2 and HC at 3% and 4%, respectively, and it performed well concerning the traffic performance outputs (its implementation allowed the number of stops to be reduced by 14%). This happens because some turbo-roundabouts along N2 (TR1/TR2) have one dedicated lane for through traffic and moderate left-turning movement which leads to a drop in capacity.

Considering site N3, the results revealed small differences between the conventional and turbo-roundabout layouts (CO_2, CO and HC decreased 1%, 1% and 4% respectively with the proposed corridor while idling situations were reduced by more than 4%). The relative good performance of turbo-roundabout corridor at the N3 occurred for two main reasons: *1*) moderate proportion of right-turning traffic in some main entries; *2*) almost turbo-roundabouts have two lanes for through traffic.

Table 5.3 Emissions and traffic performance parameters (with standard error of the mean) per scenario

Site ID	Corridor Layout	Emissions				Traffic Performance	
		CO_2 [kg]	CO [g]	NO_X [g]	HC [g]	Travel Time [s/veh]	Total Stops
N1	Turbo	374 (2.7)	913 (9.2)	1,220 (25.1)	65.4 (1.6)	77.2 (0.2)	495 (15.3)
	Conventional	373 (2.3)	908 (7.0)	1,219 (19.3)	65.3 (1.2)	75.9 (0.2)	513 (10.9)
N2	Turbo	254 (1.7)	542 (3.4)	383 (2.5)	14.0 (0.1)	70.9 (0.4)	353 (8.4)
	Conventional	247 (1.6)	530 (3.2)	376 (2.7)	13.5 (0.2)	68.4 (0.5)	303 (8.9)
N3	Turbo	356 (2.5)	747 (5.2)	534 (3.7)	19.8 (0.1)	82.4 (0.1)	295 (8.0)
	Conventional	353 (2.7)	739 (5.5)	530 (4.0)	19.0 (0.2)	80.0 (0.3)	283 (10.3)

Note: *Average values using 15 random seed runs*

Legend: *Shadow cells indicate that the difference between conventional and turbo-roundabout output measure was not statistically significant (p-value < 0.05)*

The overall analysis showed that the differences in the average emissions between layouts ranged from 1% to 4% between N1 and N3 sites. In such cases, the difference in global and local pollutant emissions between turbo and conventional roundabout was not statistically significant at the 5% significance level.

Despite these results, it is not clear if turbo-roundabouts will perform efficiently under high-congestion flows. The impact of spacing on emissions had been demonstrated previously, and therefore the optimal placement of turbo-roundabouts could bring additional traffic benefits.

5.4.2.3. Impact of corridor geometric and operational characteristics

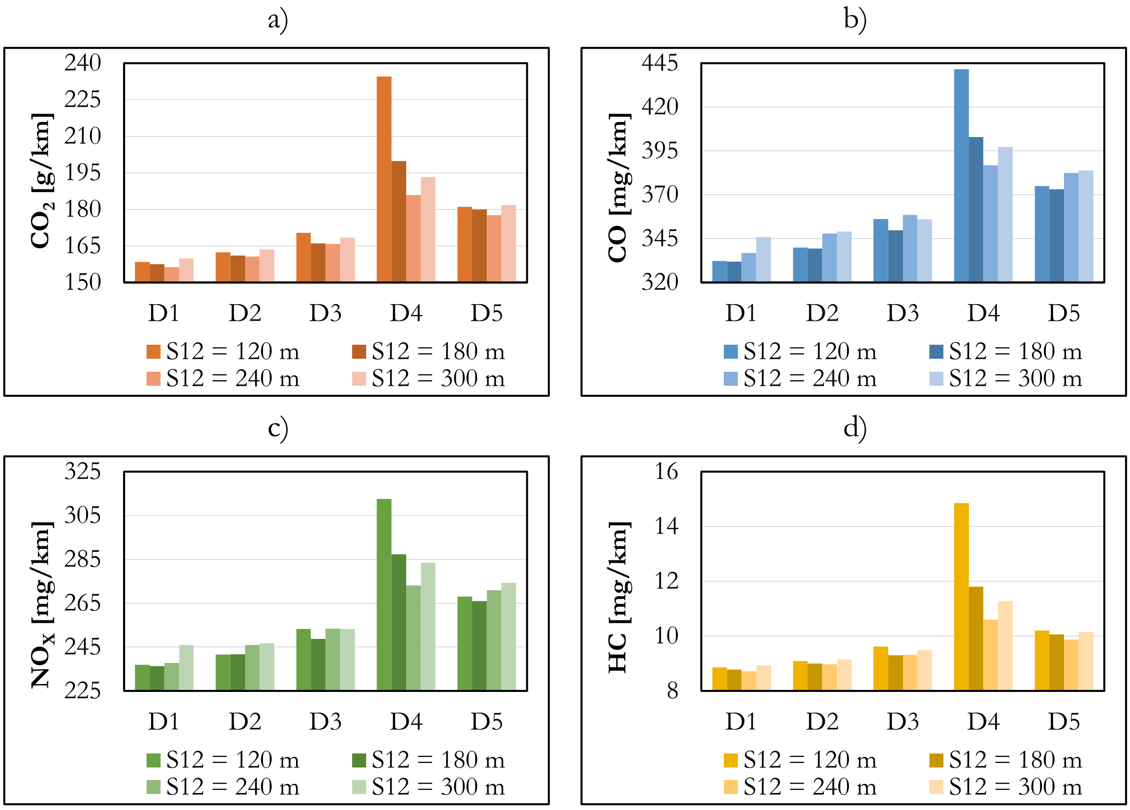
This section evaluated the emission impacts of varying the spacing values between adjacent turbo-roundabouts at the N3 site. Two motivations supported the choice of N3 in this analysis: *1*) low average spacing; and *2*) moderate traffic flow at the minor entries.

Four hypothetical spacing values between TR1 and TR2 were applied, assuming that TR2 was moved along the mid-block sub-segment. These were 120 m, 180 m (current spacing), 240 m and 300 m. For each spacing value, five traffic scenarios were defined: observed traffic flow (D1); expected traffic growth of 20% (D2), 40% (D3) and 60% (D4); and directional splits of 30-70 at the TR2 entrances, in which each set of values indicates the percentages of right-turning and through traffic movements, respectively (D5).

Figure 5.5 displays the effect of varying the spacing between TR1 and TR2 at the above scenarios on CO_2, CO, NO_X and HC emissions. Some conclusions are:

- No significant differences in emissions were found among spacing values with traffic demand levels of D1, D2 and D3;
- Vehicles generated the lowest CO_2 emissions per kilometer by adopting a 240 m of spacing between TR1 and TR2 regardless of traffic scenarios (D1-D5);
- Emissions increased markedly near saturation (D4) at low-spacing values (120 m and 180 m). For instance, if one adopted a spacing solution of 240 m, then one could save up to 8%, 4%, 5% and 11% in CO_2, CO, NO_X and HC emissions, respectively when compared to the existing spacing;
- Under uncongested conditions (D1-D3), the current spacing between TR1 and TR2 was a particularly effective means to reduce local pollutant emissions. This occurred because vehicles attained higher speeds at the mid-block section between TR1 and TR2 when the spacing was 240 m, and therefore they had sharper acceleration and deceleration rates;
- Locating TR2 farther from TR1 (300 m of spacing) negatively affected emissions upstream of TR3. There were increases in emissions of about 4% for CO and NO_X compared with that of the existing conditions (180 m and D1);
- The emissions per unit distance increased when 70% of vehicles at TR2 went through (D5). This was particularly true in highest spacing between TR1 and TR2 (3% more CO and NO_X than those obtained with the existing spacing).

The change in spacing can be impossible in practical terms in many corridors due to site-specific land use constraints. Rather than changing spacing, this section stressed the importance of analyzing the location of adjacent turbo-roundabouts (prior their construction or in existing facilities) to avoid high traffic congestion or pollutant emission levels.



Legend: *S12: Distance from the downstream exit lane of TR1 to the upstream yield lane of TR2*

Figure 5.5 Emission trends with demand and spacing scenarios: a) CO_2 per kilometer; b) CO per kilometer; c) NO_X per kilometer; d) HC per kilometer.

5.5. Conclusions

This paper explored the impact of turbo-roundabout corridors on traffic performance and vehicular emissions. Traffic flow along with vehicle dynamic data were collected from three real-world turbo-roundabout corridors in the Netherlands.

The study first introduced a methodology to quantify the hotspot emission locations for these interdependent turbo-roundabouts based on empirical data. The downstream (acceleration) sub-segments were identified as the emission hotspots both in absolute terms (overall contribution on emissions exceeded 30%) and per unit distance.

The evaluation of global and local pollutants emissions for different values of spacing demonstrated the influence of this parameter on the spatial distribution of emissions along turbo-roundabout corridors ($R^2 > 0.70$).

The consequences of comparing existing turbo-roundabout corridors to equivalent two-lane roundabout corridors were further carried out in a simulation environment. This study used the VSP and EMEP/EEA methodologies, which uses the speed trajectories from the VISSIM traffic model, to estimate the emissions generated from vehicles. The results showed that vehicles through the turbo-roundabout corridors had on average higher travel time than under the two-lane roundabout corridors. Nevertheless, the environmental benefits of converting turbo-roundabout into two-lane roundabouts in two sites was not statistically significant at p-value <0.05. This was mostly due to the fact that some turbo-roundabouts had two lanes available for through traffic over the entire corridor.

However, when the demand reached saturation, closely spaced turbo-roundabouts resulted in a marked increase in overall corridor emissions. For instance, an additional decrease of emissions between 4%-11% (depending on the pollutant) may be expected by adopting a spacing of 240 m when compared to a spacing of 180 m.

Thus, it is clear that the implementation of series of turbo-roundabouts along corridors as an alternative to traditional two-lane roundabout corridors results in small increases in emissions and traffic performance parameters in almost sites. It should also be mentioned that the safety benefits of turbo-roundabouts are well recognized, which makes them a feasible solution to be implemented in other European countries and in the US.

The use of turbo-roundabouts along arterials requires a further analysis prior to their construction. This is especially important when site-specific operational (high-traffic levels or high proportion of left-turning) or geometric (land use constraints that result in short spacing) concerns are presented.

Future work must be conducted to study the possibility of replacing turbo-roundabouts on an existing corridor by other turbo-roundabout layouts, and assess their impact on traffic performance and vehicular emissions.

5.6. Acknowledgments

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6. MULTI-OBJETIVE ANALYSIS ON CORRIDORS

Until this phase, the thesis centered on the characteristics and operational aspects of roundabout corridors. Now, the focus was to improve corridor efficiency by designing some key elements such as the crosswalk location along mid-block section between closely-spaced roundabouts, and suitable traffic control and spacing between intersections.

6.1. Assessment of the crosswalk location on an urban corridor with closely-spaced roundabouts

PUBLISHED

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Abstract

Midblock pedestrian crossing areas between closely spaced roundabouts can affect traffic operations and may result in a trade-off between capacity, environment, and safety benefits. Even though research has been conducted on the impacts of traffic performance on pedestrian crosswalks located at isolated roundabouts, few studies have focused on how pedestrian crosswalks between closely adjacent roundabouts affect traffic operations. A microsimulation approach was used to examine the integrated effect of a pedestrian crosswalk on traffic delay, carbon dioxide emissions, and relative speed between vehicles and pedestrians at different locations between closely spaced two-lane roundabouts. The main purpose of the study was to develop a simulation platform of traffic (VISSIM), emissions (vehicle-specific power), and safety (surrogate safety assessment model) to optimize such variables. The fast non-dominated sorting genetic algorithm NSGA-II was mobilized to identify an optimized set of pedestrian crosswalk locations for the roundabout exit section along the midblock segment.

One acceptable solution that provided a good balance between traffic performance, emissions, and pedestrian safety benefits was locating the crosswalks at 15, 20, and 30 m from the exit section. Even at low pedestrian demand, crosswalk effectiveness (as determined by capacity and environment) gradually decreased near the circulatory ring delimitation (<10 m). Findings suggest that crosswalks in the midblock segment (55 to 60 m from the exit section) also must be considered, especially under high traffic demand.

Keywords: Pedestrians crosswalks; Roundabout corridors; Microscale modeling; Multi-objective optimization

6.1.1. Introduction and Research Objectives

Roundabouts can provide a safe environment for nonmotorized users such as pedestrians and bicycles (1). Roundabouts convey these benefits because they encourage slower speeds of travel, provide shorter crossing distances, and allow pedestrians crossings in only one direction of travel at a time (2). Operational information as well as information about the energy and safety impacts of roundabouts usually is collected at isolated intersections, but the impact on roundabout corridors is different. The problem of how pedestrian crosswalks affect roundabout capacity may arise under conditions of intense pedestrian or vehicle flow (2, 3).

A great deal of research has been conducted in the United States (US) and Europe over the past decade to study the effects of pedestrian crosswalks at isolated intersections. Most design manuals suggest locating the crosswalks 10 to 15 m downstream of the exit junction to avoid affecting traffic flow in the circulatory ring. However, few scientific studies support this empirical range (2, 4, 5). The influence of crosswalks near roundabouts at isolated intersections usually is measured as capacity (or delay) or safety.

The Highway Capacity Manual 2010 (HCM) provides some relationships for determining reduced traffic capacity at roundabouts resulting from the influence of pedestrian streams but does not cover the case of a roundabout closely adjacent to one or more roundabouts (6). Several authors have developed analytical models to address vehicle-pedestrian interaction in roundabouts installed at isolated intersections in the US and Europe (7-9).

The main safety focus of the current literature has been the assessment of pedestrian accessibility requirements. Several studies have demonstrated that roundabouts bring challenges to pedestrians, especially those who are visually impaired (10, 11). Thus, interest has increased in testing different treatments at roundabouts to increase pedestrian safety (12, 13). However, these studies did not include the analysis of crosswalks between adjacent roundabouts.

The research on emissions and fuel consumption in roundabouts is extensive but does not consider the influence of pedestrian crosswalks at isolated intersections or at a corridor level (14-17). Similarly, the few studies carried out in roundabout corridors did not examine the pedestrian influence on traffic operations (18, 19). Bak and Kiec evaluate the influence of various midblock pedestrian crossing types (as overall delay for vehicles and pedestrians) but do not include crosswalks in midblock segments between adjacent roundabouts (20).

A literature review revealed that some studies were concerned with the influence of pedestrian crosswalks on the available capacity in isolated roundabouts. Others focused on crosswalk accessibility to improve pedestrian safety. None addressed the influence of midblock pedestrian crossings between closely spaced adjacent roundabouts on traffic operations – that is, on capacity or delay, vehicular emissions, and pedestrian safety. In summary, the literature lacks a method that integrates all of the previously mentioned concerns.

The motivation of this research is to assess the impact of pedestrian crosswalks in roundabout corridors on traffic delay, emissions, and pedestrian safety. In conjunction with a multi-objective genetic algorithm, emissions and safety are used to study the impact of crosswalk locations in a microsimulation platform of traffic. The effects of pedestrian crosswalk locations were hypothesized to lead to a trade-off analysis among the selected variables. Under high traffic and pedestrian demands, a crosswalk near a roundabout was expected to have a negative impact on emissions and delays and to be safe for pedestrians because vehicles drive at low speeds. In contrast, far crosswalks (close to mid-block) were expected to improve capacity and emissions but be less safe for pedestrians because vehicles drive at 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 versus traffic delay, crosswalk location versus carbon dioxide (CO_2) emissions, and crosswalk location versus pedestrian safety]. This study also is 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 follow:

- What is the impact of crosswalk location along the midblock segment of a roundabout corridor on vehicle delay, CO_2 emissions, and pedestrian safety with variations in traffic and pedestrian demand?
- For the same scenarios, where are the best locations to build a pedestrian crosswalk in a roundabout corridor?

6.1.2. Methodology

The core idea of the proposed methodology was to develop a microsimulation framework to assess pedestrian crosswalks on vehicle delay and emissions as well as pedestrian safety. The methodology proceeded in five steps, illustrated in **Figure 6.1**. First, data were collected in the study domain (**Sections 6.1.2.1** and **6.1.2.2**). Then, a microscopic traffic model was used to model and evaluate the network for the baseline scenario (**Section 6.1.2.3**). After that, several scenarios were defined and evaluated (**Section 6.1.2.6**); for each scenario, emissions and safety were evaluated with the vehicle-specific power (VSP) methodology and the surrogate safety assessment model (SSAM). Finally, the traffic model was calibrated and validated (**Section 6.1.2.4**), then the multi-objective optimization was performed (**Section 6.1.2.5**).

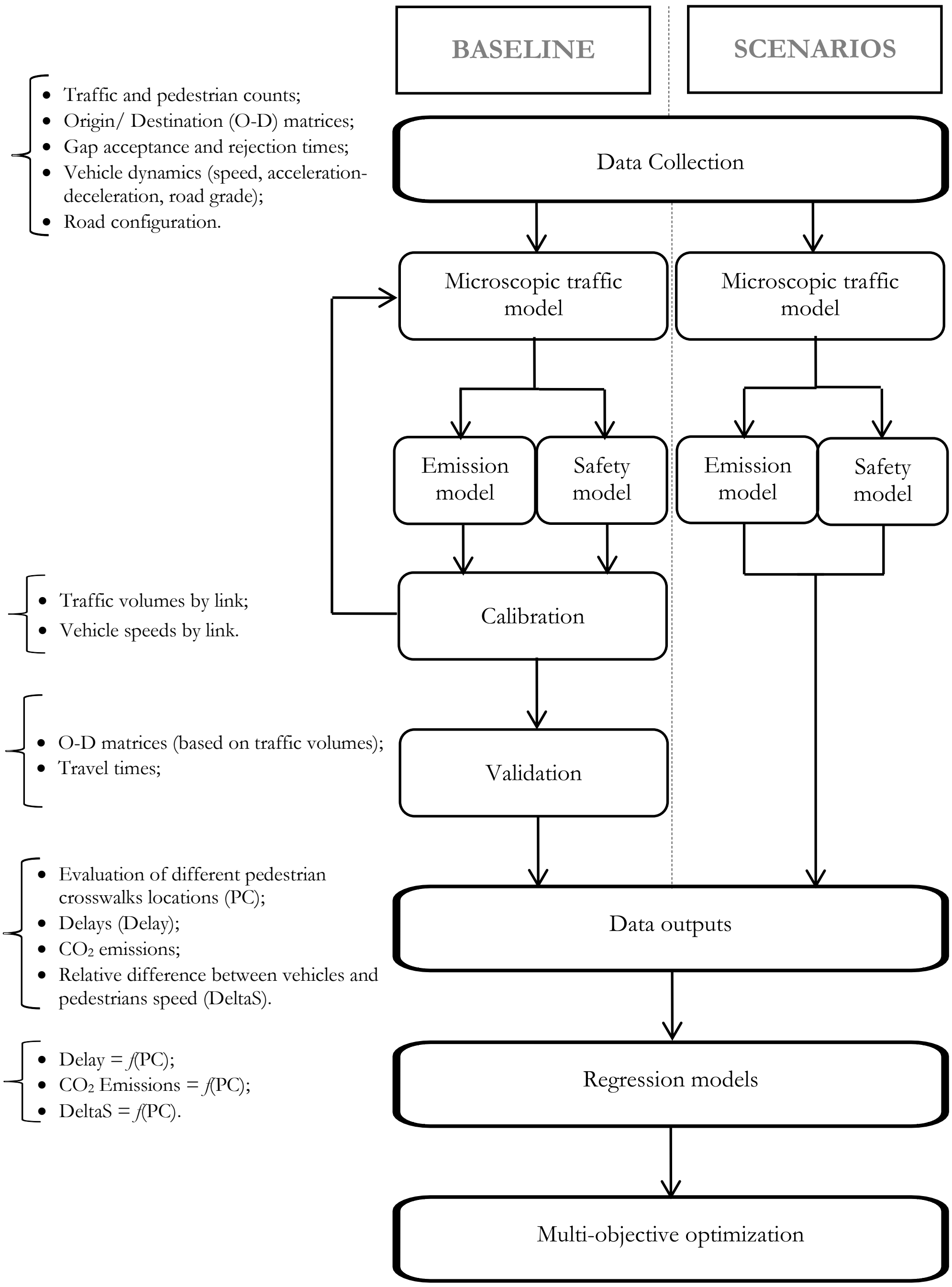

Figure 6.1 Methodological Framework (O-D = origin-destination, PC = pedestrian crosswalk location, DeltaS = relative speed).

6.1.2.1. Baseline Site

The case study consists of an urban roundabout corridor in Chaves, Portugal, which is a medium-sized European city with 41,243 inhabitants and a population density of 2,000 inhabitants/km^2 in its downtown area (21). The study corridor is 480 m long (measured from the mid-block of one roundabout to the mid-block of the adjacent roundabout) and comprises two two-lane roundabouts, one with three legs (RBT1) and one with five legs (RBT2) (**Figure 6.2**). The spacing between roundabouts (measured from the upstream yield lanes) is about 150 m. An arterial with one lane in each direction connects the roundabouts. Because of its central location and roundabout spacing, the arterial has a limited capacity of approximately 750 vehicles per hour (vph) per lane. The posted speed limit in the study area is 50 km/h. The actual location of the pedestrian crosswalk is at the upstream end of RBT2. Two explanations justify this choice: *1)* high pedestrian traffic flow (≈ 160 pedestrians per hour), and *2)* proximity to the roundabout exit section (≈ 10 m).

Site characteristics [e.g., location, circulating width, inscribed circle diameters, and traffic data for each entry and exit leg] are summarized in **Table 6.1**.

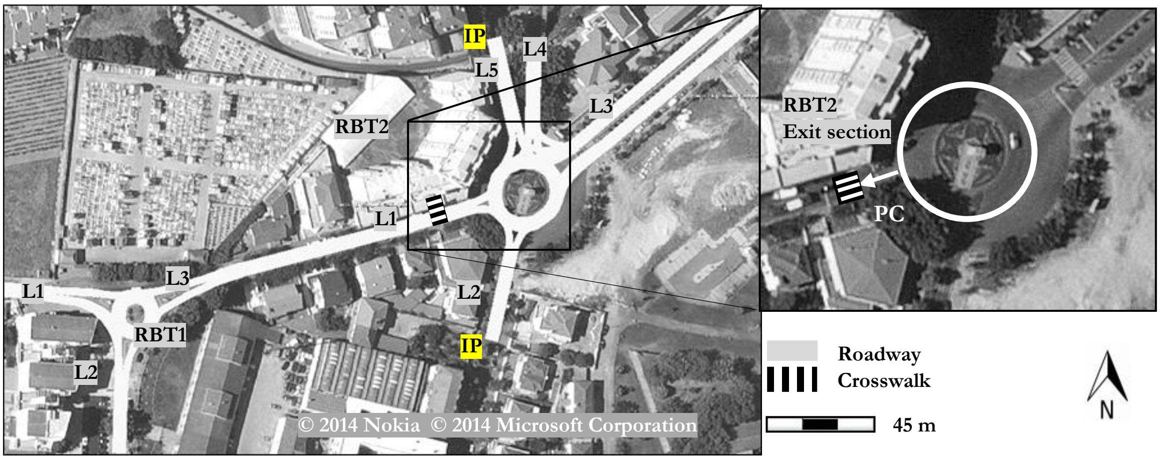

Figure 6.2 Aerial view of selected corridor in Chaves, Portugal, with roundabouts (RBT1 and RBT2), legs (L), PC, coded network, and input of pedestrians (IP) or centroids.

Table 6.1 Key Characteristics of Selected Corridor

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

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

6.1.2.2. 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 were also extracted from the videotapes. Data were collected during the evening peak (4:00 to 6:00 p.m.) on three typical weekdays (Tuesday to Thursday) in February 2014 under dry weather conditions.

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

6.1.2.3. Microsimulation platform for traffic, emissions, and safety

Traffic Modeling

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

The simulation model was run for 90 min (4:30 to 6:00 pm); the first 30 min were a warm-up period, and data were extracted for only during the final 60 min. The following distribution fleet composition was considered (23): 44.7% Light Duty Gasoline Vehicles (LDGV), 34.3% Light Duty Diesel Vehicles (LDDV), and 21.0% Light Commercial Diesel Vehicles (LCDV). Other categories represented only 1.0% of traffic composition and were excluded from this analysis.

The coded network in VISSIM is depicted in **Figure 6.2**. 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).

CO_2 Emissions

The VSP method was used to estimate vehicular emissions for two main reasons: *1)* VSP allows the estimation of instantaneous emissions from second-by-second vehicle dynamics, taking the trajectory files given by VISSIM as input; and *2)* VSP includes a wide range of engine displacement values and therefore can be applied to the European car fleet (24).

VSP is a function of the instantaneous speed, acceleration and deceleration, and road grade. The VSP values are categorized in 14 modes, and an emission factor for each mode is used to estimate CO_2 emissions from LDGV<1.2L (24, 25), LDDV<1.6L (26), and LCDV<2.5L (26).

Previous research has documented the effectiveness of the VSP approach in analyzing the emissions impacts of different roundabout layouts (14, 17). Because the terrain was flat, the effect of the grade was ignored.

Safety

For the safety assessment approach, software developed by the Federal Highway Administration (FHWA) was used (27). SSAM automates traffic conflict analysis by processing vehicle and pedestrian trajectories (*.trj files). This approach has all the common advantages of simulation (e.g. safety assessment of new facilities before crash occurrence) but also has some drawbacks: current microscopic traffic models are not able to model certain crash types, such as sideswipe, head-on, or U-turn collisions (27). Vasconcelos et al. recognize that despite some limitations in the nature of traffic models, SSAM can evaluate the relative safety of different roundabout layouts (28).

For each interaction, SSAM stores the trajectories of vehicles (or pedestrians) from the traffic model, records surrogate measures of safety, and determines whether that interaction satisfies the condition to be deemed a conflict. Time-to-Collision (TTC) was used as a threshold to determine whether a given vehicle-pedestrian interaction is a conflict; the Relative Speed (DeltaS) was used as a proxy for crash severity (27). TTC is the minimum time-to-collision value observed during the interaction of two vehicles (or pedestrians) on a collision route. If at any time the TTC drops below a given threshold [2 s, as suggested for vehicle-pedestrian events (29)], the interaction is tagged as a conflict. DeltaS is the difference in vehicle (or pedestrian) speeds as observed at the moment of the minimum TTC (27).

SSAM categorizes the resulting conflicts to conflict angle (from -180° to +180°). This angle is expressed from the perspective of the first vehicle (or pedestrian) that arrives at the conflict point and indicates the approach direction of the second vehicle. A conflict angles is categorized as rear end (0º to 30°), crossing (85º to 180°), or lane change (all remaining conflict angles) (27).

6.1.2.4. Calibration and Validation

VISSIM parameters were calibrated by modifying driver behavior and vehicle performance parameters in the traffic model and examining their effect on traffic volumes and speed for each link. The main driver behavior parameters are related to car-following (average standstill distance, additive and multiple parts of safety distance), lane-change, gap acceptance (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 – minimization of Normalized Root Mean Square (NRMS) – is denoted by **Eq. 6.1**. The calibration procedure was formulated as follows (30):

$$\text{Min } NRMS = \frac{1}{\sqrt{N}} \times \sum_{t=1}^{T} \left(W \times \sqrt{\sum_{i=1}^{I} \left(\frac{v_i - \tilde{v}(\theta)_i}{v_i} \right)^2} + (1-W) \times \sqrt{\sum_{i=1}^{I} \left(\frac{s_i - \tilde{s}(\theta)_i}{s_i} \right)^2} \right) \quad \textbf{Eq. 6.1}$$

Subject to: Lower bound ≤ θ ≤ Upper bound

Where:

N = Total number of links in the coded network;
T = Total number of time periods t;
W = Weight to assign more or less value to volumes or speeds;

I = Last analyzed link;
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.

Normalization enables the consideration of multiple performance measures (in this case, link volumes and speeds). For calibration criteria, the currently accepted FHWA-recommended practice is to rely on the Geoffrey E. Havers (GEH) statistic for assessing goodness of fit. The difference between observed and estimated link volumes (vehicles or pedestrians) should be less than 4 for at least 85% of the coded links (31).

Model validation focused on comparing estimated and observed O-D matrices and travel time for a preliminary number of runs [between 10 and 20, as suggested by Hale (32)]. The GEH statistic was used to measure goodness of fit. Because crash data records were not available in the studied location, the validation procedure did not compare conflicts from SSAM and crash data. About 80% of the data was used for calibration and the remaining data for validation.

6.1.2.5. Multi-objective optimization

The Fast Non-Dominated Sorting Genetic Algorithm (NSGA-II) was adopted in this research for two main reasons: *1)* incorporating the crowding distance into the fitness function yields diversity in optimal solutions, and *2)* the binary tournament approach accommodates the selection process (33). NSGA-II has been reported as an effective algorithm for finding a good approximation of an optimal Pareto front (34).

Figure 6.3 displays the main steps of NSGA-II, which was implemented in MATLAB. A user-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 a Pareto Optimal Front (POF) and diversity in the solutions (34). The convergence to POF is based on a comparison of the sets of non-dominated solutions from various generations. The convergence is better when the number of dominated solutions is small. The diversity of the solutions is measured by estimating Spread and Uniformity Measure metrics (35). For the purpose of analysis, the delay, CO_2, the DeltaS variables are considered to have the same weight during the optimization procedure.

The maximum number of generations was set to 2,000 initially for all the test instances, and the crossover and mutation rates were set at 90% and 10%, respectively. Each scenario was run 10 times in the NSGA-II code. The outputs concerning the number of dominated solutions, Spread and Uniformity Measure, were computed for each repetition. After the convergence to POF was guaranteed and solution diversity was accomplished in all scenarios, an equal maximum number of generations was used.

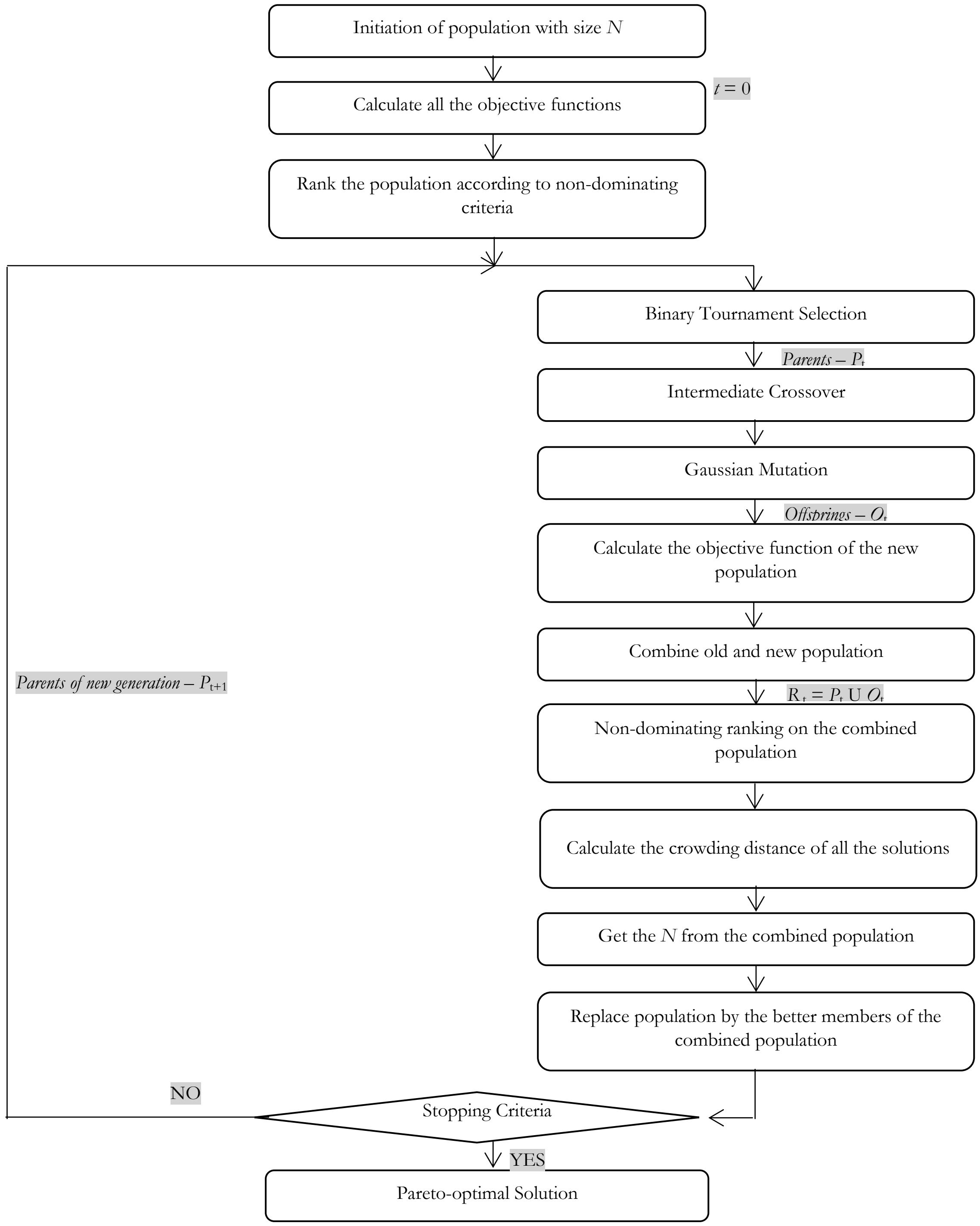

Figure 6.3 Basic structure of NSGA-II algorithm.

6.1.2.6. Scenarios

In this research, the baseline scenario was the validated simulation model with the observed demands for pedestrians (160 pedestrians per hour) and traffic (100% of demand factor). A preliminary analysis performed in the simulation demonstrated that pedestrian demands of 330 pedestrians per hour and 135% of the traffic demand initiated traffic congestion in the coded network. Thus, the effects of uniform pedestrian flows and traffic growth (motor vehicles only) were explored at two levels each: for pedestrian demand, Scenario 1 (S1) at 240 pedestrians per hour and Scenario 2 (S2) at 320 pedestrians per hour; for traffic growth, Scenario 3 (S3) at 115% of demand factor, and Scenario 4 (S4) at 130% of demand factor.

For each level, two main demand scenarios were defined. The first level evaluates how vehicle delays, emissions, and pedestrian safety change with 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 in pedestrian flows (S3 and S4). For all crosswalks locations, the authors modeled the centroids where pedestrians enter and leave at the same place in the coded network as in the baseline scenario. Also, pedestrians always walked to the crosswalk, regardless of its location.

Only crossing conflicts were considered at the selected pedestrian crosswalk. SSAM identifies not only vehicle-pedestrian conflicts but also pedestrian-pedestrian conflicts. In fact, all traffic (vehicles and pedestrians) appear in the *.trj file that SSAM uses. To address this problem, the authors filtered out any conflict for which the maximum speed was lower than 2.2 m/s (which is faster than natural walking speed). The delay and CO_2 emissions per unit distance were given from the vehicle record evaluation (22). For safety analysis, the conflicts were classified according to FHWA criteria (27).

The five scenarios (baseline and S1 through S4) were applied, assuming several possible pedestrian crosswalk locations (PCs) from 5 to 60 m in 5-m increments (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 6.2**.

Three objective functions were optimized for each scenario: delay, CO_2 emissions, and DeltaS. These functions were used as PC decision variables, subject to 5 m $\leq$ PC $\leq$ 60 m. The regression functions were PC versus delay, PC versus CO_2 emissions, and PC versus DeltaS. A set of 10 optimal solutions was considered for this analysis.

6.1.3. Results and Discussion

6.1.3.1. Calibration and Validation

Figure 6.4 shows observed and estimated traffic volumes and vehicle speeds before (with VISSIM default parameters) and after the calibration of the traffic model. The results show larger improvements for vehicle speed counts, but traffic volumes were slightly modified. After calibration, speeds improved for 75% (n = 29) of the links. The remaining speeds were close to initial speed values. Analysis of the calibration procedure also demonstrated that speed values were more sensitive to changes in the model parameters than link values were.

Table 6.2 summarizes the traffic calibration results obtained for NRMS, the GEH statistic, and the total link volumes before (default) and after model calibration. Lane-change parameters and simulation resolution were unaffected by calibration. Results confirm that calibrated model parameters improved the GEH statistic, which was < 4 for every link and satisfied the calibration criteria. The NRMS 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.

For validation, observed and estimated O-D traffic flows at the roundabouts were compared with 15 random seed runs (32). Of the 34 loop detectors (all feasible movements for RBT1 and RBT2), 88% reached GEH values < 4. These validation results suggested a good degree of consistency for all cases (31). The travel time analysis (with 200 floating car runs) revealed small differences between observed and estimated data (1% to 3% for all movements). Similar results were achieved in the remaining movements.

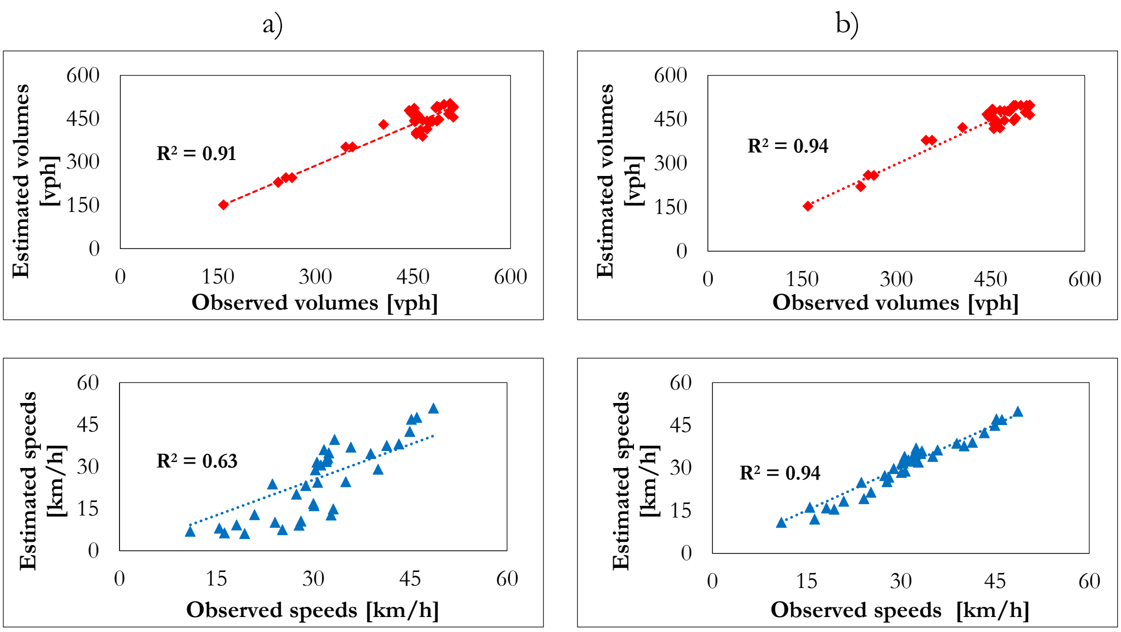

Figure 6.4 Observed versus Estimated traffic volumes [top] and vehicle speeds [bottom]: a) default model; and b) calibrated model.

Table 6.2 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	< 4 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	< 4 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: *Observed total link volume was 16,112 vph; weight factor (W) was set to 0.5.*

6.1.3.2. Regression Models

Figure 6.5 depicts the results for each of the scenarios by varying the pedestrian crosswalk location from 5 and 60 m the RBT2 exit section. Various models were tested to identify whether the predictive regression models were a good fit for the analyzed data.

Results indicated that, regardless of pedestrian demand (baseline, S1, and S2), delays and CO_2 emissions per unit distance were meaningful for pedestrian crosswalks placed less than 10 m from the RBT2 exit section (**Figure 6.5** a-b, d-e). On average, delays and CO_2 emissions at those locations were 25% and 10% higher, respectively, than average values recorded at the farthest crosswalks (PC > 20 m). Also, the difference between vehicle and pedestrian speeds (DeltaS) was small for the crosswalks near the circulatory ring (PC < 15 m) and increased gradually for crosswalks close to the mid-block segment (PC > 30 m). From that location, DeltaS did not vary significantly (~30 km/h). This result may be due to the low vehicle speeds caused by not reaching cruise speeds over the mid-block section between RBT1 and RBT2.

When the traffic demand increased (S3 and S4), the impacts associated with pedestrian crosswalk location increased at locations next to the limit of the RBT2 circulatory carriageway (**Figure 6.5** j-m). Real-time visualization of the simulation revealed that locations with stocking capacities of one vehicle (PC = 5 m) or two vehicles (PC = 10 m) tend to generate queues in the exit zone that extend to the circulation ring of RBT2. As a result, traffic from RBT2 backs up almost to RBT1. Delay and CO_2 emissions per unit distance at those locations confirmed these findings. However, vehicles drove at low speeds and stopped at crosswalks near the RBT2 exit section, contributing to pedestrian safety improvements.

These results led to the conclusion that crosswalks near a roundabout exit section have a negative influence on both entry capacity and CO_2 emissions and induce congestion on the second roundabout, especially under high traffic demand. The trade-off between performance, environment, and safety was observed clearly as the pedestrian crosswalk moved along the mid-block section. Rather than reading the resulting outputs from the graphs, the authors used the regression equations in the NSGA-II algorithm to identify possible optimal solutions.

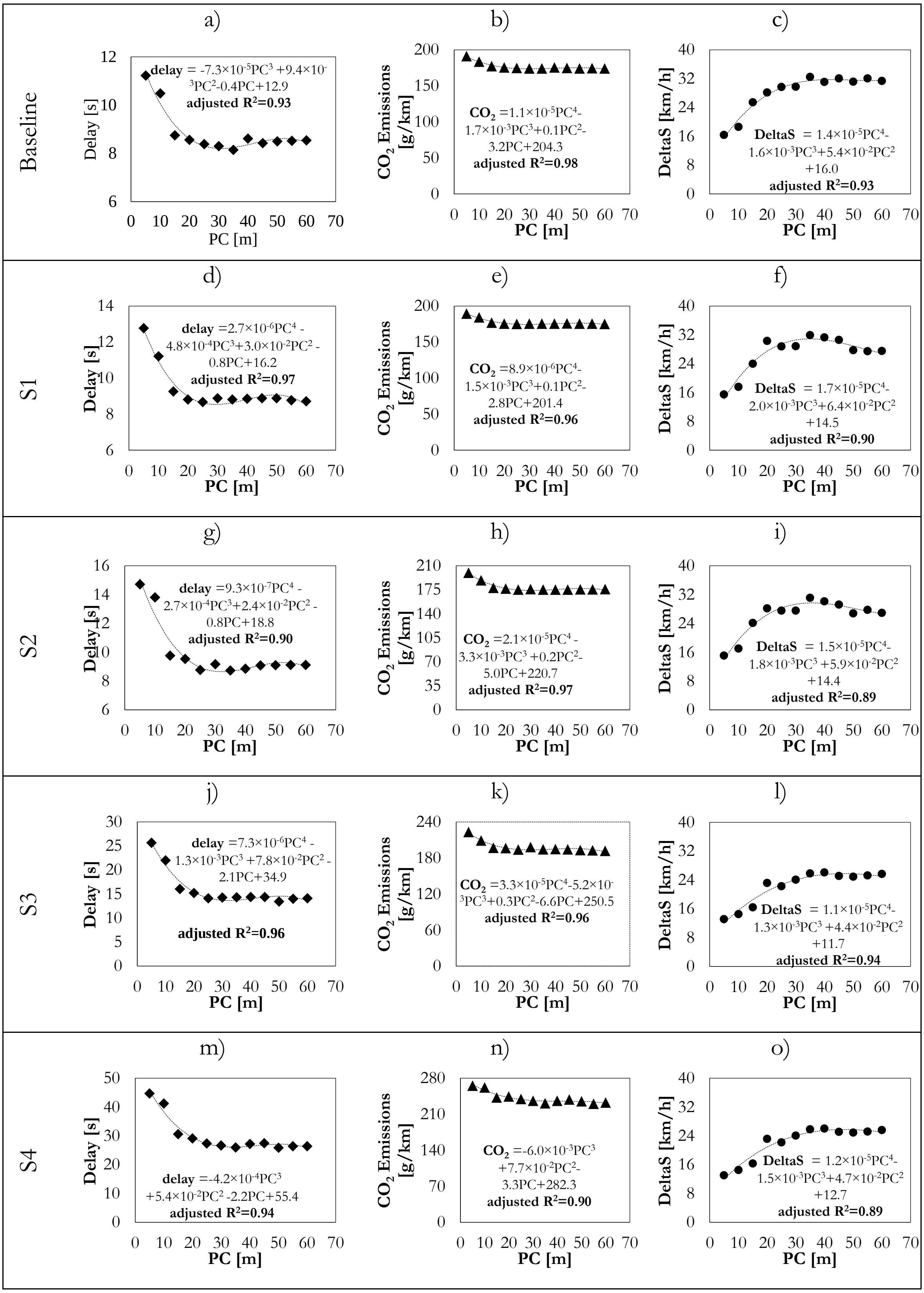

Figure 6.5 Regression models results for scenario PC versus Delay, PC versus CO_2 and PC versus DeltaS: baseline scenario (a, b, c), S1 (d, e, f), S2 (g, h, i), S3 (j, k, l) and S4 (m, n, o).

6.1.3.3. 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 pedestrian crosswalk location along the mid-block section, for each of the scenarios previously defined (baseline, S1 through S4). Analysis of the convergence to POF and the diversity of solutions indicated that 300 iterations were sufficient to reach convergence. Because each solution of the final POF did not vary much with different rate values, 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 6.3**. **Figure 6.6** illustrates the Pareto fronts estimated from the initial and final (1^{st} and 300^{th} iterations, respectively) populations. For each scenario, the objective functions (CO_2 emissions, delay and DeltaS) are presented as a function of PC in a three-dimensional scatter plot. In the baseline scenario (**Figure 6.6**-a), the approximate Pareto front moves markedly toward the bottom left, an indication that crosswalks placed more than 32 m from the circulatory ring are not good solutions for current traffic conditions. When a crosswalk placed 15 m away from the RBT2 section (Solution 6) is adopted, average delay and CO_2 emissions per unit distance decreased by 19% and 7% respectively, but DeltaS increased by no less than 37% over the lower-level solution (Solution 1). Crosswalks located 20 and 31 m from RBT2 also are proven as optimal solutions in the selected case study (**Table 6.3**). Similar results were found for S1 and S2.

In the scenarios with high traffic demand (S3 and S4), the final Pareto front moved toward the top left and bottom right, that is, the solutions associated with the crosswalks farthest from (PC = 60 m) and nearest to (PC = 5 m) the RBT2 exit section, respectively. The first case is explained by the low DeltaS values (~24 km/h) at those locations compared with the low-demand scenarios (i.e., baseline, S1 and S2; ~30 km/h). Similarly, the average values of delay and CO_2 emissions decreased as the crosswalk distance from the RBT2 exit section increased (**Figure 6.6** *j-k*, *n-m*). For instance, location of a crosswalk 60 m from the exit section (assuming the traffic conditions of S4) could save up to 43% and 13% in average delay and CO_2 emissions, respectively, whereas DeltaS increases by 74% (**Table 6.3**). In the second case, high congestion resulted in low DeltaS values near the RBT2 exit section (~14 km/h); therefore, such a location was suggested as a solution to be implemented at the arterial.

These findings indicate that the crosswalk location far from the circulatory carriageway also can be used (PC = 55 to 60 m), especially under high traffic conditions. In such cases, the effect on pedestrian safety was perceived to be slightly negative because the roundabout spacing constrains vehicle speeds at the mid-block segments. However, locating the crosswalk in farther from the downstream roundabout (e.g. PC = 80 m) affected traffic operations in the upstream roundabout. Even though the crosswalks near the exit section were undoubtedly safe for pedestrians, their practical implementation would not provide any global competition in capacity and environment. Previous research demonstrated that for high pedestrian demand (>400 pedestrians per hour) at 70% of the saturation rate, a crosswalk did not affect traffic operations when located less than 15 m from the roundabout delimitation (5).

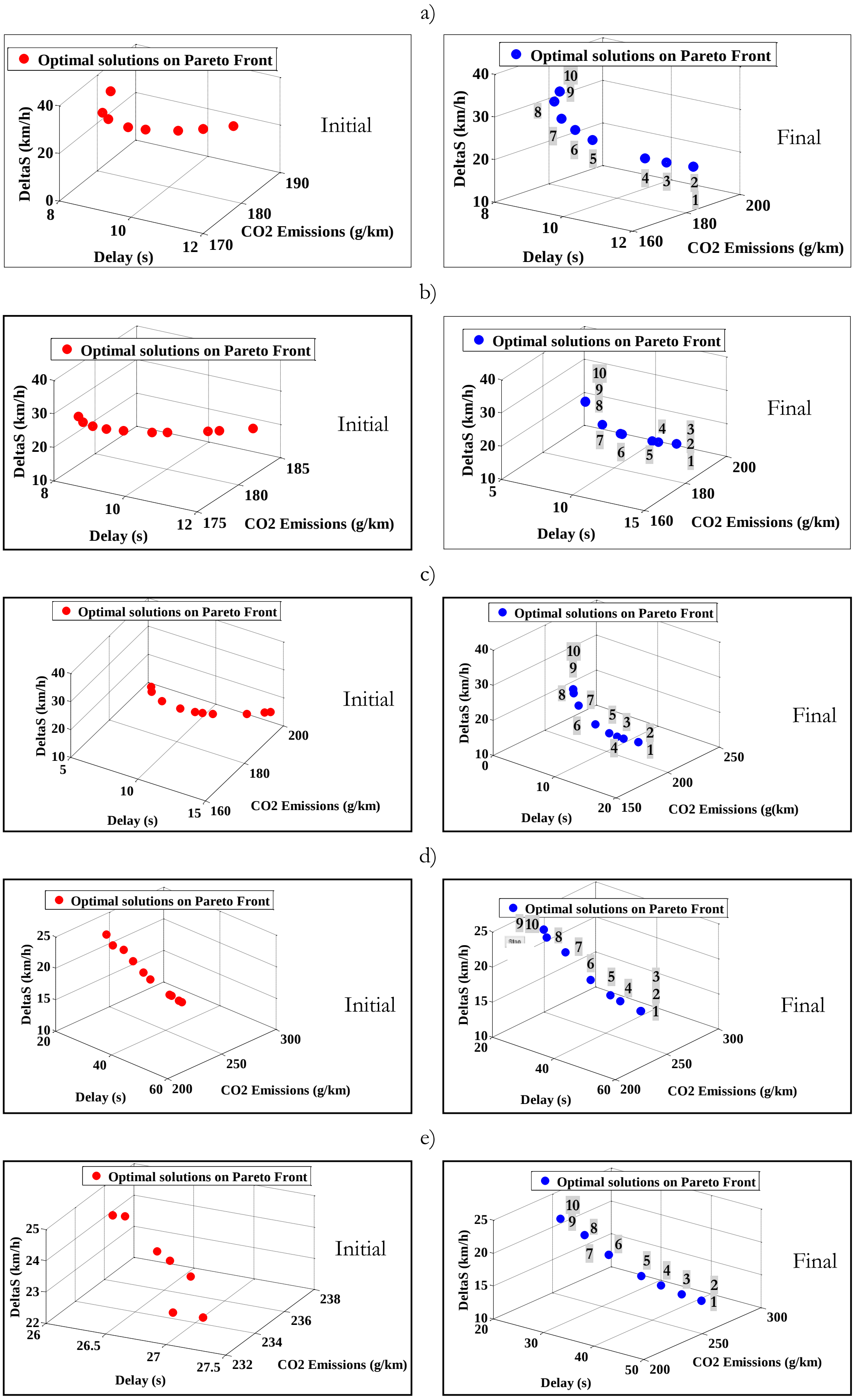

Figure 6.6 Approximate initial (left) and final (right) Pareto fronts for the four scenarios (data points are optimal solutions): a) Baseline; b) S1; c) S2; d) S3, and e) S4.

Table 6.3 Solution lists of 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

6.1.4. Conclusions

This paper explores the effects of different pedestrian crosswalk locations between two closely adjacent roundabouts on traffic performance, environment, and pedestrian safety. The microsimulation approach to analysis used a model combined with emission and safety models. Three regression models were established to express the trade-off between delay, CO_2 emissions per unit distance, and the difference between vehicle and pedestrian speeds as a function of several pedestrian crosswalk locations along the mid-block segment. As a solution algorithm for the models, NSGA-II searched for optimal solutions to the proposed problem.

Crosswalks near the circulating carriageway (< 10 m) were associated with weak performance levels and high CO_2 emissions rates. The distances of 15, 20 and 30 m were predicted to be appropriate in this interrupted traffic facility, regardless of pedestrian and traffic demands. Also, for high traffic flows, the crosswalk location near the mid-block (55 to 60 m) improved capacity and emissions values use without affecting pedestrian safety significantly.

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 and emissions are not the only considerations for the assessment of crosswalk location at roundabouts. Improved pedestrian safety remains the most important selling point of any good crosswalk location. Still, the findings in this study provide relevant information for local authorities about considering the trade-off between capacity, environment, and safety in locating a pedestrian crosswalk. Because a site's operational conditions may favor other pedestrian crosswalk locations, the models should be calibrated to the traffic, pedestrian demands, and driving patterns of the specific site.

Three main limitations must be outlined. First, only impacts on the pedestrian crosswalk were considered; others crosswalks and pedestrian patterns were excluded from this analysis. Second, specific measures that can reflect the pedestrian performance, such as delay, were absent. Third, only pedestrians walked in the crosswalk.

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

6.1.5. Acknowledgments

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6.2. Effect of roundabout corridor's design and pollutant criteria on selecting optimal crosswalk locations

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Abstract

Crosswalks located at mid-block segment between roundabouts can provide a good balance among delay, carbon dioxide (CO_2) emissions and relative difference between vehicles and pedestrians speed. However, when considering local pollutant criteria, the optimal crosswalk location may be different to that obtained for CO_2.

This paper described a multi-objective analysis of pedestrian crosswalk locations, with the objectives of minimizing delay, emissions and relative difference between vehicles and pedestrians speed. Accounting for the difference between global (e.g. CO_2) and local pollutants (monoxide carbon, nitrogen oxides and hydrocarbons) was one the main considerations of this work. Vehicle activity along with traffic and pedestrian flows data at six roundabout corridors in Portugal, one in Spain and one in the United States were collected and extracted. A simulation environment using VISSIM, VSP, and SSAM models was used to evaluate traffic operations along the sites. The Fast Non-Dominated Sorting Genetic Algorithm (NSGA-II) was implemented to further search optimal crosswalk locations.

The results yielded improvements to both delay and emissions by using site-optimized crosswalks. The findings also revealed that the spacing between intersections widely influenced the optimal crosswalk location along a mid-block section. If the spacing is low (<100 m), the crosswalk location will be approximately in 20%-30% of the spacing length. For spacing values between 140 and 200 m, crosswalks would be located at the midway position. When a specific pollutant criterion was considered, no significant differences were observed among optimal crosswalk data sets.

Keywords: CO_2, Crosswalks, Local pollutants, Multi-objective optimization, Roundabout Corridors, Spacing

6.2.1. Introduction and Literature Review

In the past few decades, many transportation authorities are progressively looking at roundabouts as an alternative solution to signalized intersections as a means to improve traffic performance, and safety for vulnerable road users such as pedestrians (2, 36). This trend has prompted the increased construction of roundabout corridors across Europe and in the United States (US). Many of these corridors are placed in commercial and residential neighborhoods, where some pedestrian activity is expected.

Previous studies have documented the influence of pedestrian streams on available vehicular capacity of the isolated roundabouts (3, 7, 37-39). Some authors suggest locating the crosswalks 10 to 15 m downstream of the exit junction to improve traffic operations (5, 6). Duran and Cheu (40) stated that entry capacity was negatively influenced by short distances between the crosswalk and the yield line. However, the afro-mentioned studies only included the analysis of crosswalks at roundabouts in isolation.

Roundabout corridors have specific operational characteristics compared with roundabouts in isolation. Fundamentally, high congested mid-block areas between adjacent roundabouts in close-proximity substantially impact vehicle speed and acceleration-deceleration patterns (1), as well as pollutant emissions on the adjacent roundabouts (41). Thus, the impact of the pedestrian crosswalks on corridors capacity may arise under conditions of short spacing intersections.

The research on traffic performance, fuel consumption and emissions in corridors with different traffic controls is extensive but did not include the influence of pedestrian crosswalks (42-45) or the impact of spacing on traffic operations (46-48). Bugg et al. (49) developed empirical models to predict arterial travel time and delay along roundabout corridors. These models neither assessed the impact of crosswalks on traffic operations nor included the emissions and safety fields on their equations.

The implementation of the crosswalk along the mid-block section between roundabouts could result in a trade-off among vehicle delay, safety and emissions. On the one side, a crosswalk near the roundabout has a negative impact on emissions and delays, and simultaneously can be safe for pedestrians since vehicles drive at low speeds. On the other side, crosswalks close to mid-block improve capacity and emissions, but could increase injury risk for pedestrians.

With these concerns in mind, Fernandes et al. (50) examined the integrated effect of crosswalk location between closely-spaced two-lane roundabouts (spacing <170 m) in the city of Chaves (Portugal) on traffic delay, carbon dioxide (CO_2) emissions and relative difference between vehicles and pedestrians speed. They found that locating the crosswalk at 15 and 55 to 60 m from the exit section provided a good balance among those outputs. The authors also recommended that the spacing between roundabouts constrained vehicle speeds at mid-block segments (50). Nevertheless, this study has two main limitations. First, one specific site was evaluated, which restricted the applicability of study's findings to other locations. Second, the authors did not assess the impacts of the crosswalk location on local pollutant emissions, which have direct effects on human health.

The available literature around this topic has focused on capacity/delay, emissions (only for CO_2 that is relevant for global warming) and safety fields separately or used limited study cases. Understanding the differences in optimal crosswalk locations between CO_2 and local pollutants in an integrated way is lacking. Still, none of the previous studies has addressed how optimal crosswalk location at mid-block segment is determined by corridor's design.

This paper discusses the integrated effect of pedestrian crosswalk location on vehicle delay, pedestrian safety, and emissions for pollutant criteria (CO_2, monoxide carbon – CO, nitrogen oxides – NO_X, and hydrocarbons – HC) in roundabout corridors. The research methodology is based on the work by Fernandes et al. (50). The optimal crosswalk locations along mid-block sections were hypothesized to vary due to differences in: *1*) geometric design of roundabouts; *2*) roundabout spacing; and *3*) pollutant type.

Thus, this research tested and verified these expectations in eight roundabout corridors from three different countries (Portugal, Spain and United States – US). Capacity, emissions and safety were used to explore the impact of crosswalk locations using a microscopic traffic model (VISSIM) together with a microscale emission methodology (Vehicle Specific Power – VSP) and safety model (Surrogate Safety Assessment Model – SSAM). A multi-objective genetic algorithm was mobilized to search site-optimal crosswalk locations, and subsequent results compared with existing crosswalk locations.

The novelty of this study is the distinction between global and local pollutants in the final set of optimal crosswalk locations along the mid-block section, and the relationship between such locations and the corridor's design features.

Therefore, this paper intends to focus on the following research questions:

- What is the optimal crosswalk location with minimum vehicle delay, emissions (both global and local pollutants) and maximum safety for pedestrians?
- How spacing between roundabouts impacts on optimal crosswalk location?

Section 6.2.2 describes the methodology used in this research. Analysis results are explained in **Section 6.2.3**, followed by the main conclusions and the limitations of this research in **Section 6.2.4**.

6.2.2. Methodology

The proposed methodology is built on a microsimulation framework to evaluate the pedestrian crosswalk on vehicle delay, pollutant emissions, and pedestrian safety. The methodology was divided in the following steps (**Figure 6.7**). First, traffic and pedestrian flows, and GPS data were collected in the selected study sites. Second, each site was coded using VISSIM microscopic traffic model and calibrated according the site-specific characteristics. Third, several operational scenarios on each studied location were defined; for each scenario, emissions and safety were analyzed using VSP methodology and SSAM model. Step four focused on the description of the multi-objective procedure.

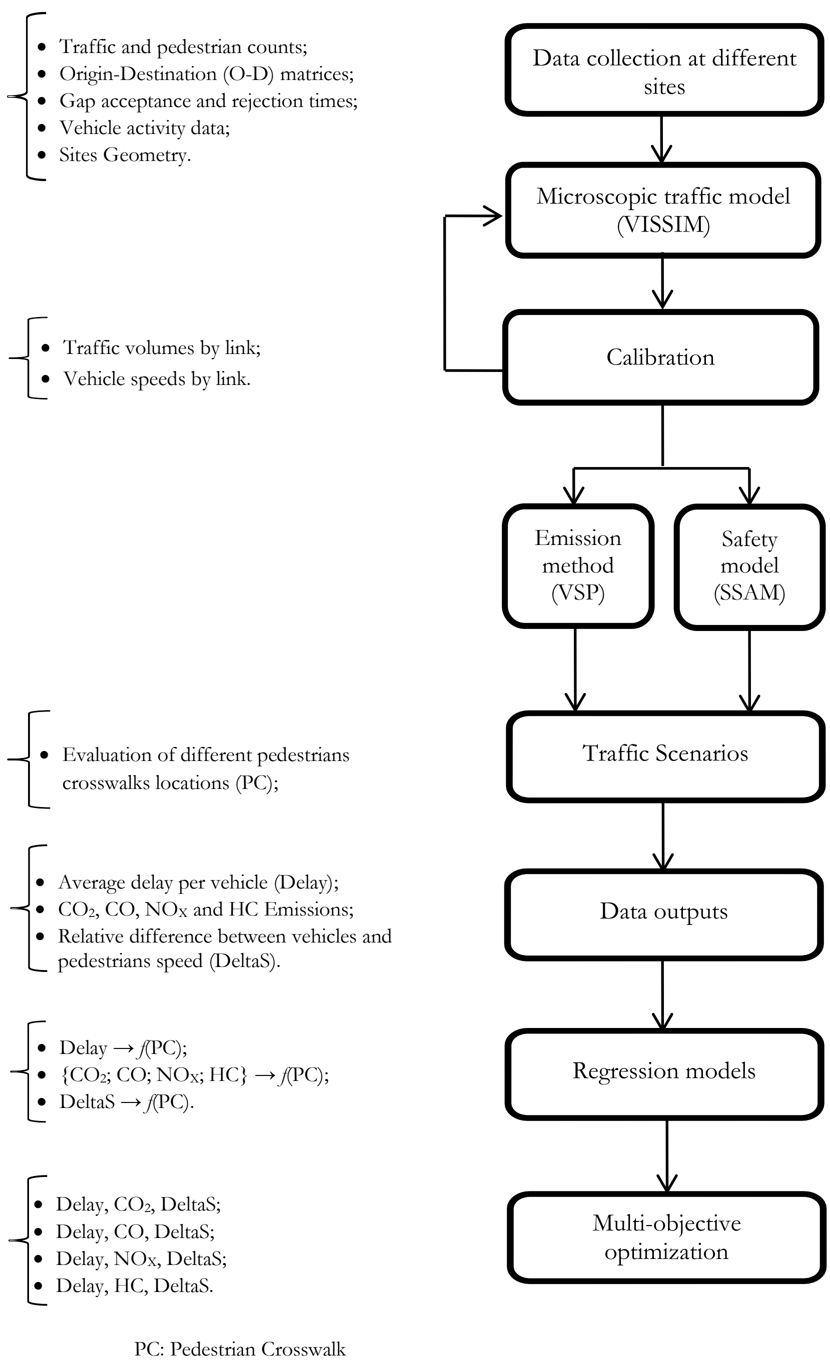


Figure 6.7 Methodological framework.

6.2.2.1. Field data collection and study sites

Data were collected at the candidate sites during the evening peak (4:00 to 6:00 p.m.) on typical weekdays (Tuesday to Thursday) from April to June 2015, and under dry weather conditions:

- Traffic flows (Passenger Vehicles, Heavy Duty Vehicles and Transit Buses);
- Pedestrian flows at the candidate crosswalks on both directions of travelling (4:00- 6:00 p.m.);
- High resolution vehicle activity data (speed, acceleration-deceleration and road slope on a second-by-second basis);
- Time-gap distributions data;
- Spacing between roundabouts;
- Posted speed limits.

Traffic and pedestrian flows, and time-gap distributions data (gap-acceptance and gap-rejection) for all turning maneuvers were collected from overhead videos installed at strategic points along the study sites. The recorded videotapes were later reviewed in research laboratory for obtaining traffic and pedestrian flows and resulting Origin-Destination (O-D) matrices. Data were recorded in 15-min time intervals.

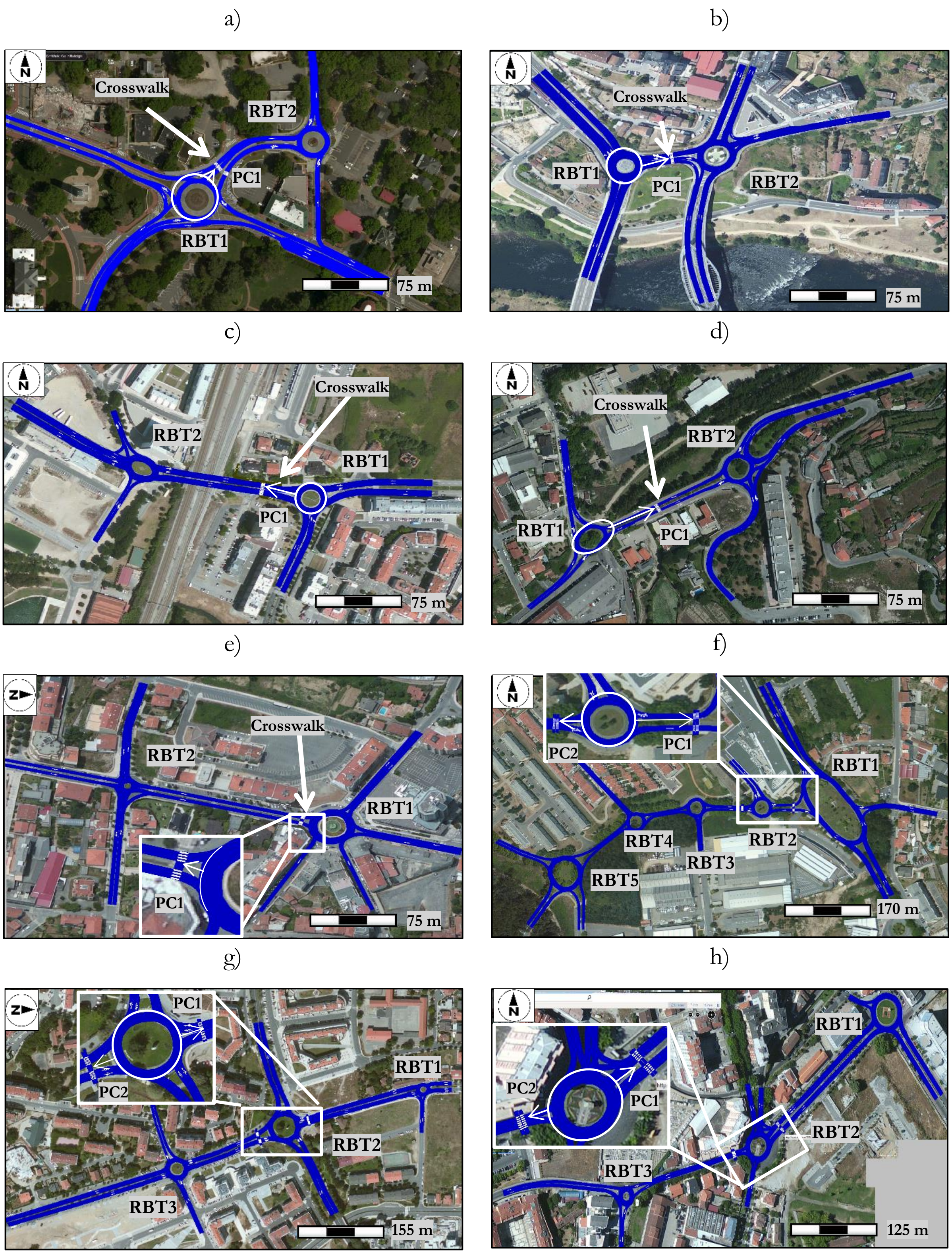
GPS Technology, in the form of an in-vehicle data logger, recorded the speed, position, latitude and longitude coordinates as well as topographic conditions of the vehicles as they traveled along the corridors (in 1-second time intervals). The GPS equipped-vehicle continuously loops through a pre-defined route extending beyond the beginning and end of the corridor (through movements).

To generalize the applicability of the methodology and range of the dataset, the authors selected sites for data collection representing a variety of characteristics and conditions. Using these considerations, six urban roundabout corridors in the North and Center of Portugal (PT1, PT2, PT3, PT4, PT5 and PT6), and one in Spain (SP1) and in the US (US1) were selected. The sites included the following range of attributes: *1*) number of roundabouts per corridor between 2 and 5; *2*) spacing ranged from 58 m to 200 m; and *3*) posted speed limits lower than 50 km/h.

The team elected one crosswalk at the corridors with 2 roundabouts (**Figure 6.8**a-e) and two crosswalks for other sites (**Figure 6.8**f-h). The pedestrian activity at other crosswalks did not affect site-specific traffic operations (negligible pedestrian flows) and therefore was ignored. Almost sites are located on relatively flat grades. The exception was the PT4 site (**Figure 6.8**-f) where crosswalks were placed on a high slope arterial (>5%).

Table 6.4 lists each site where data were collected, including geographic location, number of entering lanes by approach, number of circulating lanes in the roundabouts, number of entry and exit legs, circle inscribed diameter, spacing between roundabouts (measured from the downstream exit lane from one roundabout to the upstream yield lane of the adjacent roundabout in the direction of travel) based on the procedures presented in the research of Bugg et al. (49), presence of restrictive median, location for the candidate crosswalks from the circulatory ring delimitation, and crosswalk GPS coordinates.

The peak arterial traffic and pedestrian flows data are also presented in **Table 6.4**. 800 GPS travel runs for each through movement (around 100 at each site) were extracted and identified for this research (440 km of road coverage over 16 h) (51).



Note: *PC1 and PC2 are the distances from the RBT2 exit section to the candidate crosswalks*

Figure 6.8 Aerial view of the Candidate Sites: a) US1; b) SP1; c) PT1; d) PT2; e) PT3; f) PT4; g) PT5; h) PT6 [Source: https://www.bing.com/maps/].

Table 6.4 Summary of Study Sites

City	Site ID	Rbts. ID	Number of entering lanes	Number of circulating lanes	Number of entry/exit legs	Circle Inscribed Diameter [m]	Spacing [m]	Crosswalks Location [m]	Crosswalk Treatment solution	Crosswalk GPS Coordinates	Peak pedestrian flow [p/h]	Peak arterial flow [vph/lane][a]
Raleigh, NC	US1	RBT1	1/2	1	4/4	36	80	7	Raised	35°47'10.75"N 78°39'43.87"W	110	480
		RBT2	1	1	3/2	30						
Orense	SP1	RBT1	2/3	2	3/3	38	58	30	Not Raised	42°20'49.5"N 7°52'28.6"W	85	315
		RBT2	2	2	4/4	45						
Aveiro	PT1	RBT1	2	2	3/3	41	150	33	Raised	40°38'26.7"N 8°38'27.4"W	110	590
		RBT2	1/2	2	4/4	41 and 32[b]						
Guimarães	PT2	RBT1	1	1	3/3	41 and 26[c]	140	55	Raised	41°26'39.6"N 8°16'59.4"W	120	235
		RBT2	1	1	4/4	36						
Oliveira de Azeméis	PT3	RBT1	1	2	4/4	48	160	7	Raised	40°50'16.9"N 8°28'47.0"W	195	630
		RBT2	1	1	4/4	29						
São João da Madeira	PT4[d]	RBT1	1/2	2	4/4	126 and 61[b]	64	27	Raised	40°53'13.1"N 8°29'27.6"W	120	465
		RBT2	1	1	3/3	39	67	12[e]	Raised	40°53'13.07"N 8°29'31.03"W	75	345
		RBT3	1	1	3/3	36	72	-		-	-	445
		RBT4	1	1	3/3	36	100	-		-	-	340
		RBT5	1	1	4/4	56	-	-		-	-	-
Viseu	PT5	RBT1	1/2	2	3/3	24	200	13	Raised	40°38'58.68"N 7°54'44.23"W	65	275
		RBT2	2	2	4/4	56	160	17[e]	Raised	40°38'55.9"N 7°54'43.0"W	135	585
		RBT3	1/2	2	4/4	40	-	-		-	-	-
Chaves	PT6	RBT1	1	2	3/3	45	185	15	Raised	41°44'39.80"N 7°28'14.06"W	165	265
		RBT2	1/2	2	5/5	34	105	10[e]	Not Raised	41°44'38.8"N 7°28'16.5"W	180	515
		RBT3	2	2	3/3	23	-	-		-	-	-

[a] *Arterial traffic at the mid-block areas between roundabouts;*

[b] *Oval roundabouts; therefore, there are two values for the inscribed diameter;*

[c] *Roundabout RBT1 has two semi-circles;*

[d] *There are only two crosswalks between downstream of RBT1 and the upstream of RBT5;*

[e] *Distance from the RBT2 exit section.*

6.2.2.2. Microsimulation platform for traffic, emissions, and safety

Traffic modelling

VISSIM software package was selected to simulate traffic operations (22) for four main reasons: *1*) modelling reliable pedestrian-vehicle interactions at roundabout corridors (50); *2*) defining parameters of driving behavior for roundabouts such as critical gaps and headways (22, 52); *3*) calibrating a wide range of parameters to set faithful representations of the traffic on a corridor level for capacity and emissions' purposes (42, 50); and *4*) storing and exporting of both vehicle and pedestrian trajectory files that can be used by external applications to assess emissions and safety (22).

The simulation experiments in each site were based on simulation runs of 75 min (4:45-6:00 p.m.). A 15 min (4:45-5:00 p.m.) warm-up time was included in each run to allow traffic to stabilize before collecting data for the remaining 60 min. The coded network in VISSIM is depicted in **Figure 6.8**. Link speeds and flows (traffic and pedestrian) were collected for all of these links. An average pedestrian walking speed value of 1.34 $m.s^{-1}$ was adopted for this research (6).

Emissions

Vehicular emissions were calculated using VSP methodology (53). VSP, an indicator of engine load, accounts for engine power demand associated with changes in both vehicle potential and kinetic energies, aerodynamic drag, and rolling resistance (54). VSP values estimated at 1 Hz are categorized in 14 modes, and an emission factor for each mode is used to estimate vehicular CO_2, CO, NO_X and HC emissions from different vehicle types.

The main advantages of using VSP are: *1*) it allows estimating instantaneous emissions based on a second-by-second vehicle activity data, taking as input the trajectory files given by VISSIM; *2*) it includes the impact of different levels of accelerations and speed changes on emissions (55); *3*) and it is an useful explanatory variable for estimating variability in emissions (56).

Thus, emissions estimates using VSP methodology were based on vehicle dynamic data (speed, acceleration-deceleration and slope) gathered from VISSIM. Excel data sheets were developed to compute second-by-second vehicle dynamics data from VISSIM output. To reflect the local car fleet compositions, the total emissions were calculated considering the following distributions:

- Portuguese Sites: 44% of Gasoline Passenger Vehicles (GPV) with engine size <1.2l, 35% of Diesel Passenger Vehicles (DPV) with engine size <1.6l, and 21% of Light Diesel Duty Trucks (LDDT) with engine size <2.5l (23);
- Spanish Site: 41% of Gasoline Passenger Vehicle (GPV) with engine size <1.2l, 51% of Diesel Passenger Vehicle (DPV) with engine size <1.6l, and 8% of and Light Diesel Duty Trucks (LDDT) with engine size <2.5l (57);
- US Site: 39% of "Tier 1" Passenger Cars (T1 PCs) and 61% of "Tier 2" Passenger Cars (T2 PCs) (58).

The average emission rates for pollutants CO_2, CO, NOx and HC by VSP mode of the above vehicles types are reported in the following studies: GPV (25), DPV and LDDT (26), and T1 and T2 (PCs) (59). Other categories represented only 2% of traffic composition and were excluded from this analysis.

Safety

SSAM software application was developed by a research team in SIEMENS and sponsored by the Federal Highway Administration (FHWA). SSAM uses several algorithms to identify conflicts from space-time vehicles trajectory files (*.trj file) produced by microscopic simulation models as VISSIM. For each vehicle-to-vehicle (or pedestrian) interaction SSAM computes surrogate measures of safety and determines whether or not that interaction fulfils the criteria to be deemed a conflict (27).

This approach has all the common advantages of simulation such as the safety evaluation of new facilities before their implementation, or controlled testing environments. However, notwithstanding the simplicity of user interface, SSAM has two main drawbacks. First, current microscopic traffic models are not able to model specific crash types such as head-on, sideswipe or U-turn related collisions. Second, the probability of each automated conflict turning into a crash cannot be determined by SSAM (27).

The research team used Time-to-Collision (TTC) as a threshold to establish whether a vehicle-pedestrian interaction is a conflict and the relative difference between vehicles and pedestrians speed (DeltaS) as a proxy for the crash severity (27). TTC is the projected time until two vehicles (or a vehicle with a pedestrian) would collide if they keep the same trajectory route with unchanged direction and speeds. If at any time the TTC drops below a given threshold [2 s, as suggested for vehicle-pedestrian events (29)] the interaction is tagged as a conflict. DeltaS is the difference in vehicle (or pedestrian) speeds 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°): rear end if *0º<conflict angle<30*°; crossing conflict if *85º<conflict angle<180*°; or is otherwise a lane change conflict. This angle is expressed from the perspective of the first vehicle (or pedestrian) that arrives at the conflict point and indicates the approach direction of the second vehicle (27).

To address the problem associated with pedestrian-to-pedestrian conflicts (60), the research team filtered out any conflict where the maximum speed was lower than 2.2 $m.s^{-1}$ (which is faster than natural walking speed).

Model Calibration and Validation

Data collected in all sites were used to calibrate and validate the traffic simulation model. About 80% of the data were used for calibration to develop and fit the traffic model parameters, and the remaining data used for validation to assess the effectiveness of the model calibration.

Calibration of VISSIM parameters was first made by modifying driver behavior and vehicle performance parameters, and by examining their effect on traffic volumes and speeds for each link. The main driver behavior parameters of VISSIM included car-following parameters (average standstill distance, additive and multiple parts of safety distance), lane-change parameters, gap acceptance parameters (minimal gap time and minimal headway), desired speed distributions and simulation resolution (22).

These parameters were optimized using a genetic algorithm (Simultaneous Perturbation Stochastic Approximation – SPSA) to minimize Normalized Root Mean Square – NRMS (objective function) (30). The modified chi-squared statistics Geoffrey E. Havers (GEH) was used as calibration criteria. The main features of using GEH are the following: *i*) it incorporates both absolute and relative differences in comparison of estimated and observed traffic flows; *ii*) it avoids divisions by zero; and *iii*) it is independent of the order of the values (61). Fifteen simulation runs were then performed for each testing scenario, as suggested by Hale (32). Further details about this procedure can be found in the following studies (30).

Model validation focused on comparing estimated and observed flows (traffic and pedestrians), speeds, and average travel time. GEH and Mean Absolute Percent Error (MAPE) statistics were used to measure goodness of fit (61).

6.2.2.3. Scenarios

Baseline scenario is the calibrated model with the observed pedestrian and traffic demands. For all crosswalks locations, the research team modeled the centroids where pedestrians enter and leave in the coded network in the same place as the actual pedestrian location. Also, pedestrians always walked to the crosswalk.

For each site, baseline scenario was applied, assuming several possible pedestrian crosswalk locations along the mid-block section: *1*) from the downstream RBT1 to the upstream of RBT2 for corridors with 2 roundabouts; and *2*) from the circulatory ring of the RBT2 to the upstream of RBT3 and RBT1 on the remaining sites. In the first set of corridors (US1, SP1, PT1, PT2 and PT3), crosswalks were moved in 5-m increments [each increment allows an extra stocking capacity of 1 vehicle (5)]. In the second set of corridors (PT4, PT5 and PT6), nearly 25 PC1 and PC2 combinations along the mid-block section were explored by site applying 5-m increments relatively to the roundabout exit section.

After that, a relationship between pollutant emissions, delay and DeltaS, and different crosswalk locations (PC1 – corridors with 2 roundabouts; PC2 – corridors with more than 2 roundabouts) was established, as depicted in **Figure 6.8**. During this phase, various regression models were tested to identify whether the predictive regressions models were a good fit for the evaluated data (62).

6.2.2.4. Multi-objective optimization

Objective Functions

On the basis of the scenarios presented above, the following multi-objective model was constructed to minimize pollutant emissions, vehicle delay and the relative difference between vehicles and pedestrians speed.

For a given midblock pedestrian crosswalk location and site, the first and second objectives of the model mostly reveal the vehicle driver's viewpoint, which is to minimize CO_2, CO, NO_X and HC emissions per unit distance generated by vehicles (**Eq. 6.2**) and the average delay of each vehicle trip (**Eq. 6.3**) along the overall network:

$$\min = \frac{\sum_{m=1}^{N_m} F_{mj}}{T_D} \qquad \textbf{Eq. 6.2}$$

Where: m = Label for second of travel (s); j = Source pollutant; F_{mj} = Emission factor for pollutant j in label for second of travel m (g/s); N_m = Number of seconds (s); T_D = Total distance travelled by vehicle (km).

$$\min = d_i^v \qquad \textbf{Eq. 6.3}$$

Where: d_i^v = control delay by vehicle (s/veh).

The third objective function is devoted to the perspective of the pedestrian safety, with the goal of minimizing relative difference between vehicles and pedestrians speed (DeltaS) which is computed from SSAM (**Eq. 6.4**). DeltaS was obtained from crossing conflicts at the candidate pedestrian crosswalk (27).

$$\min = \text{DeltaS} \qquad \textbf{Eq. 6.4}$$

Where: DeltaS = magnitude of the difference in vehicle and pedestrian speeds (km/h).

Decision Variables

The decision variables are PC1 and PC2. They were measured from the circulatory ring delimitation of RBT2 to the limit of crosswalk (see **Figure 6.8** for more details).

Constraints

Eq. 6.5 represents the available range of spacing between roundabouts (see **Table 6.4**) which constitutes the principal constraint for the multi-objective optimization:

$$5 \leq S \leq S_{\max} \qquad \textbf{Eq. 6.5}$$

Where: $S_{\max}$ = maximum spacing length of the analyzed site that allows a stocking capacity of 1 vehicle before the upstream of exit lane of the adjacent roundabout (m).

Solution Approach

Four multi-objective tests were optimized for each site: *1*) delay-CO_2-DeltaS; *2*) delay-CO-DeltaS; *3*) delay-NO_X-DeltaS and *4*) delay-HC-DeltaS. The regression functions were PC (PC1 or PC2 depending on the site) versus delay, PC versus CO_2 emissions, PC versus CO emissions, PC versus NO_X emissions, PC versus HC emissions, and PC versus DeltaS.

The solution of a multi-objective model is always located in its Pareto optimal (non-dominated) set. The Fast Non-Dominated Sorting Genetic Algorithm (NSGA-II) (33) was adopted in this research for six main reasons: *1*) less computational complexity; *2*) elitist approach; *3*) emphasis on the non-dominated solutions during the process; *4*) diversity preserving mechanism; *5*) no requisite to consider a sharing parameter; and *6*) real number encoding (33). The standard flowchart of NSGA-II displayed in **Figure 6.9** was used.

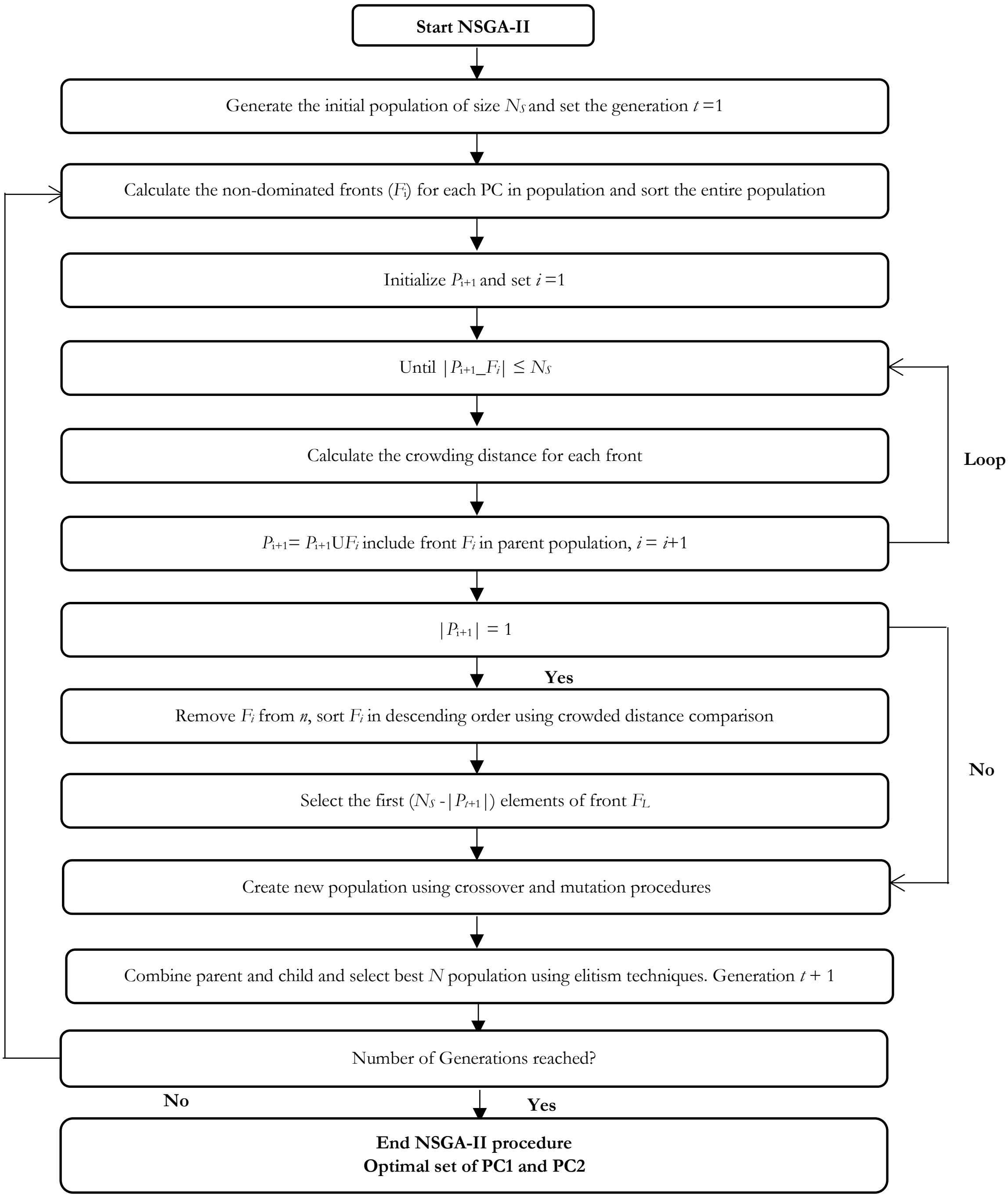


Figure 6.9 Flowchart of solution algorithm based on NSGA-II.

Sensitivity analysis on the NSGA-II parameters (population size, maximum number of generations, and mutation and crossover rates) was performed before optimization to ensure the diversity in the solutions and the convergence to Pareto Optimal Front (POF) (34)

All objective variables are considered to have the same weight during the optimization procedure. NSGA-II does not take into account the different units and magnitudes of the measures involved during its procedure. This means that the set of optimal values includes values that will minimize emissions, delay and relative different between vehicles and pedestrians speed regardless of the magnitude or units of the output measure.

6.2.3. Results and discussion

6.2.3.1. Model Calibration and Validation

Summary statistics of the VISSIM calibrated model at the selected sites are presented in **Table 6.5**. The model used 15 random seed runs (32) and was based on the paired estimated-observed flows and speeds in each link. The NRMS, the GEH and MAPE goodness of fit measures, as well as average travel time for through movements are provided. Lane-change parameters were marginally unaffected by the calibration while a simulation resolution of 10 time steps per simulation seconds (second-by-second vehicle record data) was used in all sites (22).

The findings showed a good fit between estimated and observed data using a linear regression analysis. Specifically, applying the site-calibrated values, R^2 values higher than 0.90 and 0.75 were produced for estimated traffic flows and speeds, respectively, against observed data. This meant that the estimated data explained more than 75% variation in the field measurements. Additionally, the calibrated critical gap times (2.9-4.2 s depending on the site) reflected countries driving habits, as presented elsewhere (63). The outputs of **Table 6.5** showed improvement of the GEH statistic with calibrated model parameters. More than 85% of the links achieved a GEH values less than 4, thereby satisfying the calibration criteria (31), while MAPE values for the speeds ranged from 6% to 14% between PT4 and PT3 sites, respectively. The maximum average travel time difference [using 150 floating car runs (31) by each through movement] was recorded at the PT3 site for south-north movement (~10%).

Table 6.5 Summary of calibration for the traffic model with adjusted parameters

Site ID	Parameter	Value	NRMS	GEH	R^2[a]	MAPE	Travel time [sec]
US1	Average standstill distance (m) Additive part of safety distance Multiple part of safety distance Minimal gap time (s)	0.9 1.0 1.1 4.3	0.549	< 4 for 93 % of the links	Flows: 0.95 Speeds: 0.85	Flows: 3.3% Speeds: 11.1%	Observed NS: 51.1±10.6 Estimated NS: 54.0±3.3 Observed SN: 41.6±7.0 Estimated SN: 44.4±2.5
SP1	Average standstill distance (m) Additive part of safety distance Multiple part of safety distance Minimal gap time (s)	1.0 1.2 1.4 3.4	0.307	< 4 for 96 % of the links	Flows: 0.94 Speeds: 0.81	Flows: 2.9% Speeds: 10.2%	Observed WE: 50.5±5.2 Estimated WE: 52.6±2.0 Observed EW: 55.1±9.3 Estimated EW: 50.9±1.5
PT1	Average standstill distance (m) Additive part of safety distance Multiple part of safety distance Minimal gap time (s)	1.1 0.9 1.8 2.9	0.479	< 4 for 91% of the links	Flows: 0.92 Speeds: 0.76	Flows: 6.0% Speeds: 12.8%	Observed WE: 51.9±3.6 Estimated WE: 51.2±1.6 Observed EW: 47.1±5.0 Estimated EW: 48.6±2.6
PT2	Average standstill distance (m) Additive part of safety distance Multiple part of safety distance Minimal gap time (s)	1.1 1.3 1.8 3.1	0.174	< 4 for 96 % of the links	Flows: 0.91 Speeds: 0.88	Flows: 7.0% Speeds: 9.4%	Observed WE: 50.1±3.8 Estimated WE: 52.3±1.5 Observed EW: 52.0±1.7 Estimated EW: 49.0±2.2
PT3	Average standstill distance (m) Additive part of safety distance Multiple part of safety distance Minimal gap time (s)	1.0 1.0 1.2 3.1	0.355	< 4 for 95 % of the links	Flows: 0.93 Speeds: 0.80	Flows: 3.4% Speeds: 13.7%	Observed NS: 61.9±6.0 Estimated NS: 58.1±3.4 Observed SN: 59.9±5.6 Estimated SN: 53.6±2.0
PT4	Average standstill distance (m) Additive part of safety distance Multiple part of safety distance Minimal gap time (s)	1.0 0.9 1.3 3.3	0.247	< 4 for 92 % of the links	Flows: 0.92 Speeds: 0.86	Flows: 5.0% Speeds: 6.4%	Observed WE: 87.5±6.7 Estimated WE: 89.9±1.3 Observed EW: 83.9±7.5 Estimated EW: 89.1±1.9
PT5	Average standstill distance (m) Additive part of safety distance Multiple part of safety distance Minimal gap time (s)	1.1 1.0 1.3 3.2	0.232	< 4 for 92 % of the links	Flows: 0.93 Speeds: 0.85	Flows: 2.8% Speeds:8.6%	Observed NS: 90.2±3.0 Estimated NS: 92.3±2.2 Observed SN: 89.9±5.2 Estimated SN: 87.7±1.0
PT6	Average standstill distance (m) Additive part of safety distance Multiple part of safety distance Minimal gap time (s)	1.0 1.2 2.2 3.2	0.410	< 4 for 100 % of the links	Flows: 0.95 Speeds: 0.88	Flows: 4.6% Speeds: 10.4%	Observed WE: 82.6±9.3 Estimated WE: 85.6±2.1 Observed EW: 91.3±6.5 Estimated EW: 86.9±1.7

a Linear regression analysis between the estimated and the observed flows and speeds on each coded link;

Notes: *WE – west to east movement: EW – east to west movement: NS – north to south movement; SN – south to north movement*

6.2.3.2 Sites traffic operations analysis

This section quantified and compared vehicle delay, pollutant emissions (CO_2, CO, NO_X and HC) per unit distance, and DeltaS by site with the current crosswalk locations. Delay and vehicle activity data such as speed, acceleration-deceleration and slope on a second-by-second basis were given from the vehicle record tool of the VISSIM model (22) while DeltaS was computed in SSAM (27).

Site-specific operational, emissions and safety outputs are summarized in **Table 6.6**. Several conclusions about the effect of crosswalk location can be drawn. (*i*) crosswalks near the roundabout exit section (US1, PT3 and PT6) generate the highest CO_2 emissions per unit distance and the lowest DeltaS values, which agrees with the previous study conducted by (50); (*ii*) PT3 and PT6 sites result in weak traffic performance and high emission levels among Portuguese sites, mostly because of the high pedestrian flows and the low spacing between roundabouts; (*iii*) mid-block crosswalks from the PT1 and PT2 sites cause the highest speeds differences between vehicles and pedestrians when compared to the remaining sites; (*iv*) the arterial where crosswalk is located at the SP1 site has 10% and 65% less traffic and pedestrians flows, respectively than the equivalent arterial at the PT1, but vehicles generate higher emissions per unit distance for local pollutants (more than 15%).

Table 6.6 Specific-site output measures with existing crosswalk locations

Site ID	Capacity	Emissions				Safety
	Delay [s/veh]	CO_2 [g/km]	CO [mg/km]	NO_X [mg/km]	HC [mg/km]	DeltaS [km/h]
US1	7.8	170	478	121	32.79	22.0
SP1	7.9	129	189	414	7.21	23.0
PT1	8.3	122	153	340	6.19	27.0
PT2	3.8	105	130	277	4.61	26.1
PT3	10.1	140	185	415	6.61	21.4
PT4	10.7	114	146	320	5.74	22.8
PT5	12.5	120	155	340	6.11	24.0
PT6	11.2	174	194	419	7.82	22.8

Next section describes the optimization of current crosswalk locations to assess their performance. The main purpose of this step is to improve the above outputs (delay, pollutant emissions and DeltaS). The results will then be compared with the existing crosswalk locations.

6.2.3.3. Multi-objective optimization

This section presents the main results of the multi-objective optimization of crosswalk locations. The parameters used in NSGA-II are summarized below:

- The population size (set of optimal solutions) is 10;
- The maximum number of generations is 1,000;

- The crossover rate is 90%;
- The mutation rate is 10%.

These values were found appropriate to ensure the diversity in solutions and convergence to POF. **Figure 6.10** illustrates the POF involved through the course of the optimizations for corridors with two roundabouts by pollutant criteria. For each site, a three-dimensional scatter plot with three objective functions – emissions (x-axis), delay (y-axis), and DeltaS (z-axis) – as a function of PC1 and PC2 is exhibited. Each label in **Figure 6.10** is a Pareto point that represents an optimal PC1 solution of the final POF. Its value and corresponding outputs are listed in **Table 6.7**.

The graphs confirmed the trade-off between emissions (independent of the considered pollutant) and traffic performance, and DeltaS variables from the minimal to the maximum extremes in the set of optimal PC1. Most of solutions were located at the mid-block sub-segments and near the circulatory ring of the roundabout (PC1<15 m). If one adopts the solution that minimizes global pollutant emissions of each site, then one could save between 1% and 6% in average CO_2 emissions at the SP1 and PT3 sites, respectively when compared with existing crosswalk locations.

The improvements in average delay at the PT3 site were particularly impressive. This site initially presented the closest crosswalk to the exit section and high pedestrian demand. For a chosen PC1 value of 96 m, 15% less delay could be reached compared with current location (PC1 = 7 m). As expected, crosswalks near by the roundabouts exit section yielded the lowest relative differences between vehicles and pedestrians speed. The lack of optimal PC1 values higher than 36 m at the SP1 site was possible due to right-turn bypass lane at RBT2. Accordingly, vehicles drive at low speeds along the mid-block section.

An intriguing result was detected at the PT1 and PT2 sites. In spite of having similar spacing between roundabouts, the optimal PC1 set for some pollutants was fairly different. While in the PT1 site the solutions in the approximate POFs were mostly found at the mid-block area, in the PT2 site some were located at 6 to 17 m away from the roundabout exit section. The explanations for this fact may be in the differences between sites' arterial traffic flow (PT2~235 vph/lane; PT1~590 vph/lane) together with the site's geometry. More precisely, a great portion of the vehicles is likely to be more retained by a crosswalk near the exit section under high traffic flows. Moreover, vehicles attain moderate speeds (≈35 km/h) close to the RBT1 east exit of the PT1 site (caused by small deflection angle in RBT1 east entry).

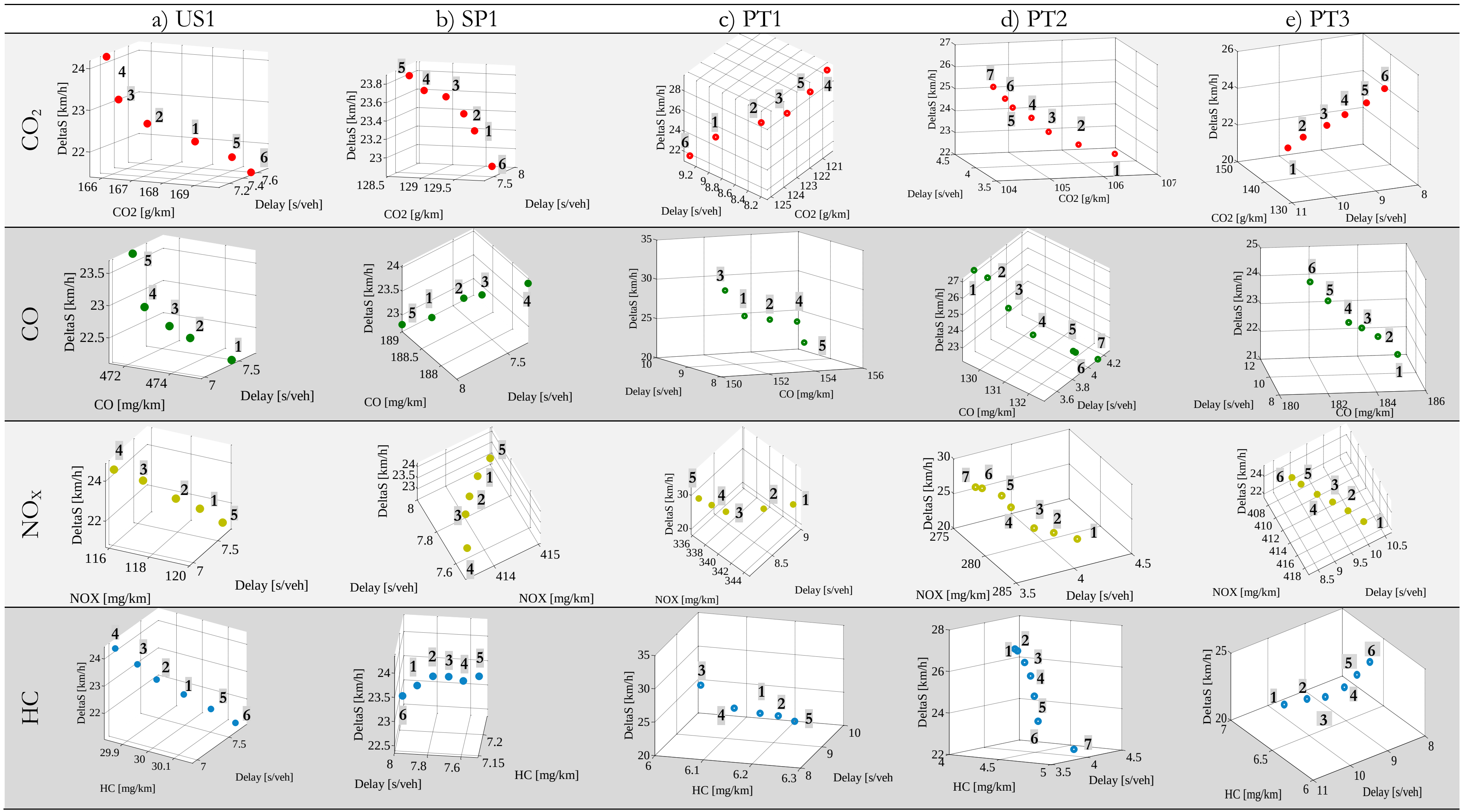


Figure 6.10 The approximate final Pareto front by pollutant criteria and site: a) US1; b) SP1; c) PT1; d) PT2 and e) PT3.

Table 6.7 Optimal crosswalk locations (PC1) of each site considering the pollutant function criteria

Site ID	Solution[a]	PC1 [m]	CO_2 [g/km]	Delay [g/veh]	DeltaS [km/h]	PC1 [m]	CO [mg/km]	Delay [s/veh]	DeltaS [km/h]	PC1 [m]	NO_X [mg/km]	Delay [s/veh]	DeltaS [km/h]	PC1 [m]	HC [mg/km]	Delay [s/veh]	DeltaS [km/h]
US1	1	8	168.0	7.5	22.1	8	475.0	7.5	22.1	8	119.1	7.5	22.1	9	30.02	7.4	22.4
	2	10	166.9	7.3	22.6	9	473.5	7.4	22.4	11	118.4	7.3	22.9	11	29.94	7.3	22.9
	3	12	166.2	7.2	23.2	10	472.9	7.3	22.6	13	117.0	7.2	23.7	13	29.89	7.2	23.5
	4	17	165.8	7.1	24.2	11	472.1	7.2	22.9	17	115.8	7.1	24.2	17	29.83	7.1	24.1
	5	70	169.2	7.5	21.8	16	471.6	7.2	23.7	72	120.0	7.6	21.4	70	30.10	7.5	21.9
	6	72	169.6	7.6	21.4		N/A				N/A			72	30.17	7.6	21.4
SP1	1	7	129.4	7.9	23.2	7	188.5	7.9	23.2	7	414.5	7.9	23.2	7	7.21	7.9	23.2
	2	8	129.3	7.8	23.4	9	188.2	7.7	23.6	8	414.1	7.8	23.4	8	7.20	7.8	23.5
	3	9	129.1	7.7	23.6	10	188.0	7.6	23.7	9	413.8	7.7	23.6	9	7.19	7.7	23.6
	4	10	128.9	7.5	23.7	15	187.6	7.3	23.9	15	413.4	7.5	23.9	10	7.17	7.6	23.7
	5	13	128.8	7.3	23.9	36	189.0	8.0	22.8	36	415.0	8.0	22.8	14	7.16	7.5	23.9
	6	36	129.6	8.0	22.8		N/A				N/A			36	7.23	8.0	22.8
PT1	1	7	124.8	9.0	24.1	35	151.4	8.3	27.1	7	343.6	9.0	24.1	7	6.21	9.0	24.1
	2	19	123.3	8.6	25.3	55	152.6	8.4	26.3	13	341.7	8.7	24.9	35	6.15	8.3	27.1
	3	35	121.0	8.3	27.1	58	150.3	8.1	30.8	35	339.4	8.3	27.1	58	6.09	8.1	30.8
	4	62	120.2	8.2	28.8	92	153.9	8.5	25.7	58	338.1	8.2	28.8	98	6.19	8.6	25.6
	5	99	122.3	8.4	25.9	115	155.3	9.3	21.8	62	337.0	8.1	30.8	105	6.23	9.3	22.4
	6	115	125.3	9.3	21.8		N/A				N/A				N/A		
PT2	1	6	106.7	4.13	22.2	6	132.6	4.13	22.2	6	283.1	4.13	22.2	6	4.79	4.13	22.2
	2	9	105.9	3.97	22.9	9	132.2	3.97	22.9	9	282.1	3.98	22.9	17	4.65	3.82	23.7
	3	11	105.3	3.92	23.6	10	132.2	3.94	23.1	13	281.2	3.86	23.4	40	4.63	3.80	24.9
	4	17	104.9	3.82	24.4	22	131.1	3.77	23.9	36	278.6	3.80	24.6	52	4.62	3.76	25.9
	5	53	104.5	3.75	25.0	36	130.0	3.80	24.6	52	277.9	3.76	25.9	63	4.61	3.69	26.6
	6	63	104.3	3.68	25.5	58	129.4	3.72	26.3	75	277.3	3.62	27.1	82	4.60	3.60	27.2
	7	83	104.0	3.58	26.2	83	129.3	3.58	27.2	83	277.0	3.58	27.2	83	4.59	3.58	27.3
PT3	1	5	142.2	10.4	21.4	6	185.3	10.2	21.6	6	416.0	10.2	21.7	6	6.71	10.2	21.6
	2	7	140.2	10.1	22.0	9	184.4	9.8	22.4	9	414.4	9.8	22.4	9	6.57	9.9	22.3
	3	12	138.7	9.6	22.8	12	183.7	9.6	22.8	12	412.9	9.6	22.8	11	6.44	9.7	22.8
	4	18	137.2	9.2	23.5	15	183.1	9.3	23.1	16	411.4	9.3	23.2	17	6.39	9.3	23.3
	5	34	135.0	8.9	24.2	29	182.2	9.0	24.0	30	410.0	9.0	24.0	30	6.37	9.0	24.0
	6	96	132.6	8.6	24.8	95	181.4	8.7	24.8	96	408.9	8.7	24.8	94	6.35	8.7	24.7

a Number of non-dominated solutions

Shadow cells indicate the minimal objective value for a specific crosswalk location

N/A: Not Applicable

In corridors with more than 2 roundabouts, the final Pareto set of PC1 and PC2 dictated optimal solutions at the mid-block sub-segment and near the RBT2 exit section, as presented in **Figure 6.11** and **Table 6.8**. Optimal solutions assigned in the bottom conducted the highest emissions/delay values and lowest DeltaS; optimal solutions allocated in the upper of the graphs corresponded to the lowest emission/delay values and highest DeltaS. Between above extremes a trade-off occurred.

PT6 site generated the highest emissions reductions (2-9% depending on the pollutant) by adopting the solution 7. The findings pointed out small differences among pollutants in the optimal data set points. However, there were some aspects on the final POF that must be emphasized. In the PT4 site few solutions were found near RBT1 circulatory carriageway (high PC1 values). This happens because vehicles from the west leg to the south leg at RBT1 drive at moderate speeds, and the south RBT1 exit leg is a downhill road (slope >5%) which has a positive influence on the vehicle speed. Several solutions at the PT4 and PT5 sites were located near the circulatory ring. This can be explained by the differences of traffic and pedestrian flows between RBT1/RBT2 and RBT2/RBT3, in which in turns allows traffic to be less affected by crosswalks installed close to the RBT2 exit section.

Three general points were outlined from above findings. First, optimal crosswalk locations were mostly found at 5 to 20 m from the downstream roundabout exit section and along the mid-block segment. Second, the set of optimal crosswalk locations did not substantially vary from both the global and the local pollutants. Third, crosswalks in a same corridor (e.g. PC1 and PC2) presented different optimal locations along the respective mid-block segment.

This suggests that the spacing between roundabouts could have an important effect on the optimal crosswalk location along the mid-block section. Previous research conducted in this topic (41) demonstrated that, under short spacing values, drivers were not able to attain cruise speeds at the mid-block section and emissions per unit distance were consistently high. However, this study did not include the influence of pedestrians in the traffic stream. This subject is then addressed in the following section.

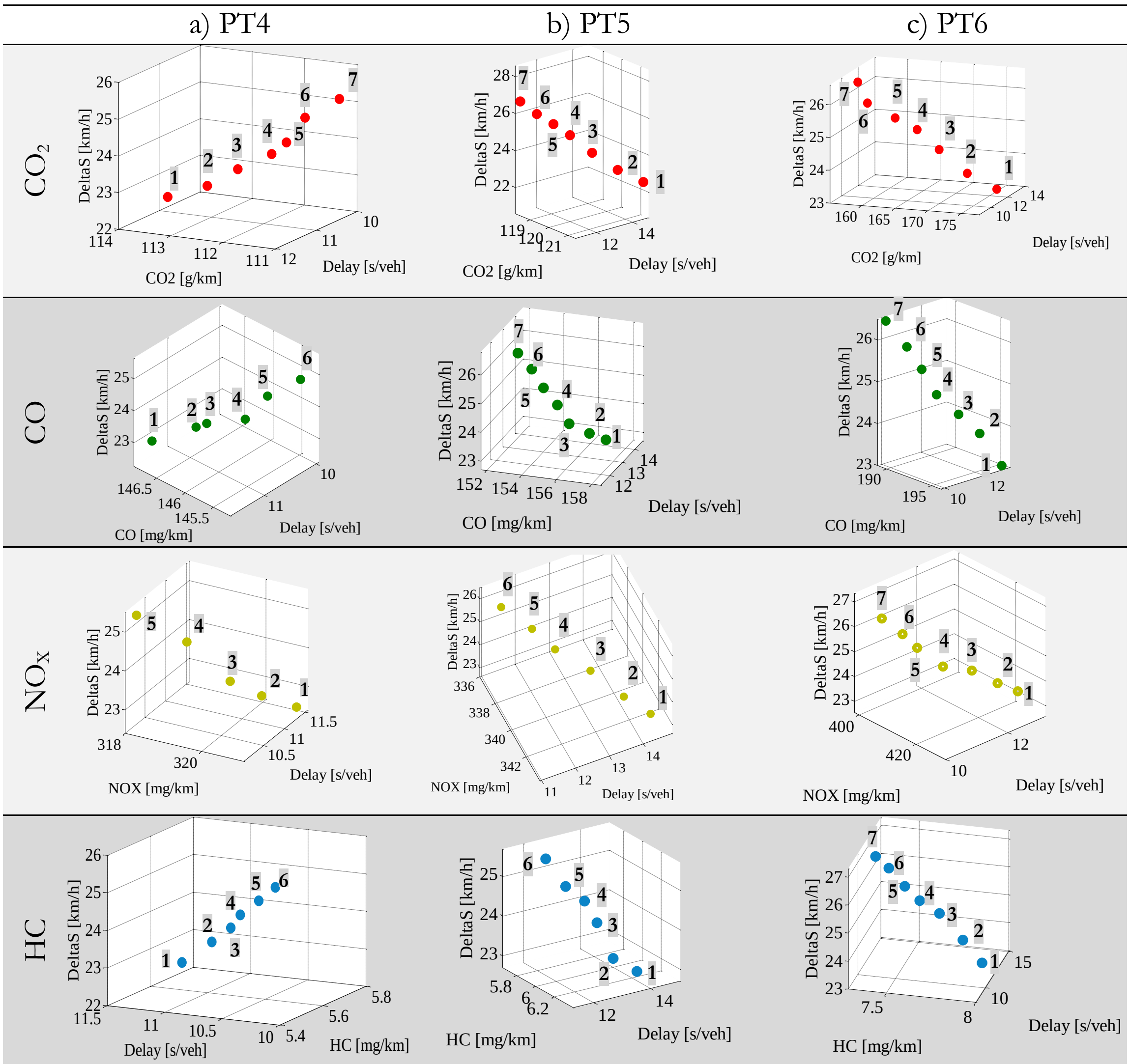


Figure 6.11 The approximate final Pareto front by pollutant criteria and site: a) PT4; b) PT5; and c) PT6.

Table 6.8 Optimal crosswalk locations (PC1 and PC2) of each site considering the pollutant function criteria

Site ID	Solution[a]	PC1/ PC2 [m]	CO_2 [g/km]	Delay [s/veh]	DeltaS [km/h]	PC1/ PC2 [m]	CO [mg/km]	Delay [s/veh]	DeltaS [km/h]	PC1/ PC2 [m]	NO_X [mg/km]	Delay [s/veh]	DeltaS [km/h]	PC1/ PC2 [m]	HC [mg/ km]	Delay [s/veh]	DeltaS [km/h]
PT4	1	40/5	113.6	11.3	22.6	40/5	146.9	11.3	22.6	40/29	321.1	11.3	22.6	40/29	5.64	11.3	22.6
	2	40/6	113.0	11.1	22.9	40/26	146.6	11.1	23.0	35/12	320.4	11.1	23.0	5/22	5.62	11.0	23.3
	3	5/20	112.5	11.0	23.4	5/24	146.3	10.9	23.4	5/21	319.8	10.9	23.4	35/18	5.60	10.8	23.8
	4	35/18	112.0	10.8	23.8	35/51	145.9	10.6	23.8	35/35	319.1	10.5	24.6	35/21	5.59	10.7	24.2
	5	35/24	111.8	10.7	24.1	35/36	145.6	10.5	24.5	18/22	318.0	10.3	25.2	35/38	5.57	10.5	24.7
	6	35/40	111.6	10.5	24.7	19/24	145.2	10.3	25.2		N/A			18/23	5.54	10.3	25.2
	7	18/22	111.1	10.3	25.2		N/A								N/A		
PT5	1	5/5	121.4	14.6	22.6	5/6	156.6	14.4	22.7	5/5	342.1	14.6	22.6	5/6	6.13	14.4	22.7
	2	5/17	120.9	13.7	23.3	125/5	156.0	13.9	23.1	5/15	341.3	14.0	23.2	125/6	6.09	13.7	23.1
	3	125/11	120.3	12.9	24.2	125/8	155.2	13.4	23.6	45/130	340.5	13.2	24.3	45/51	6.04	13.3	24.0
	4	85/138	119.6	12.4	25.0	85/115	154.8	13.0	24.4	85/133	339.4	12.4	25.0	45/76	6.03	12.9	24.6
	5	200/132	119.1	12.0	25.5	85/132	154.5	12.3	25.3	200/106	338.6	11.9	25.7	85/133	5.98	12.4	25.0
	6	85/108	118.7	11.5	26.0	125/38	154.1	11.9	26.1	165/106	337.7	11.2	26.5	160/106	5.92	11.9	25.7
	7	161/108	118.2	11.1	26.6	165/97	153.6	11.5	26.8		N/A				N/A		
	8		N/A				N/A										
PT6	1	5/5	174.5	13.2	23.0	5/5	195.3	13.2	23.0	5/5	420.8	13.2	23.0	5/5	7.90	13.2	23.0
	2	5/21	170.7	12.7	23.5	5/15	194.4	12.5	23.8	5/15	419.1	12.7	23.5	5/36	7.81	12.6	23.9
	3	40/6	167.5	11.9	24.3	5/28	193.6	11.8	24.3	5/26	417.7	12.0	24.3	110/138	7.69	12.1	24.9
	4	140/103	165.2	11.1	25.0	40/115	192.7	11.1	24.8	40/113	415.3	11.3	24.7	140/9	7.60	11.3	25.5
	5	140/36	162.5	10.6	25.4	140/15	191.9	10.7	25.4	140/7	411.7	10.8	25.5	40/38	7.53	10.8	26.1
	6	75/83	159.1	10.0	25.9	110/12	190.9	10.4	25.9	110/129	409.8	10.5	26.1	75/107	7.45	10.4	26.8
	7	111/99	158.3	9.5	26.6	100/101	189.7	9.9	26.5	114/87	408.0	10.0	26.9	115/94	7.39	9.9	27.3

a Number of non-dominated solutions

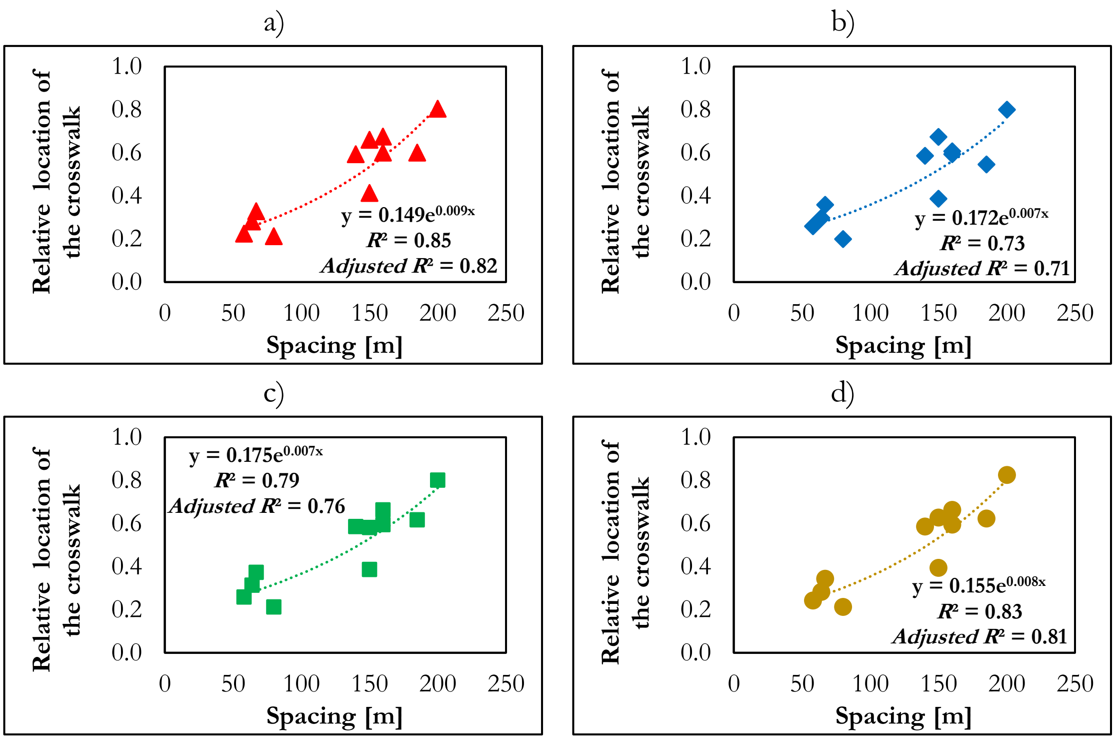
Shadow cells indicate the minimal objective value for a specific crosswalk location

N/A: Not Applicable

6.2.3.4. Relationship between optimal crosswalk locations and corridor's characteristics

With above concerns in mind, the optimal crosswalk locations which minimize global and local emissions at each site were plotted against spacing. Because spacing varies among sites, data points of crosswalk locations were normalized in relation to the spacing between roundabouts by scaling between 0 and 1. Specifically, 0 is the location at the exit (circulatory ring delimitation) lane of the RBT1 (RBT2 for corridors with more than 2 roundabouts) while 1 is at the yield lane of the upstream roundabout.

The estimated regression models for each case confirmed prior predictions, as displayed in **Figure 6.12**. There was a good regression between relative optimized locations for CO_2, CO, NO_X and HC, and spacing between roundabouts ($R^2 > 0.72$) using exponential models. For these models, the analysis of R^2 (F-test) and the analysis of coefficients for the model (T-test) resulted in *p*-values lower than 0.001. This meant that the above coefficients did not take the value 0 at any significance level, and therefore the spacing and optimal crosswalk location variables were found to be significant at confidence levels higher than 99% (62).
The scattered graphs show that for values lower than 100 m for the spacing, the relative location of the optimal crosswalk is approximately in 20%-30% of the spacing length. After that, the crosswalks are located near the midway position (value of 0.5), between 140 and 200 m of spacing.



Note: 0 is the location at the exit lane of downstream roundabout and 1 is at the yield lane of upstream roundabout considering the mid-block section where crosswalk is located.

Figure 6.12 Relative location of the optimal crosswalk: (a) minimum CO_2 versus spacing; (b) minimum CO versus spacing; (c) minimum NO_X versus spacing and (d) minimum HC versus spacing.

It should be noted that other variables such as site-specific arterial traffic and pedestrian flow at the candidate crosswalks were fitted with spacing. Nevertheless, the regressions models resulted in weak correlations between outputs.

6.2.4. Conclusions

This research examined the impact that different pedestrian crosswalk locations had on delay, CO_2, CO, NO_X and HC vehicular emissions, and on the relative difference between vehicles and pedestrians speed. The study covered eight roundabout corridors in three different countries, and conducted a multi-objective optimization of pedestrian crosswalks at different locations. The research also explored the impact of the spacing between intersections on the optimal location of the crosswalks along the mid-block section. The methodology used was executed using a microsimulation traffic model paired with an emission methodology and safety model.

The findings demonstrated that the implementation of crosswalks near the circulating roadway (<10 m), which represented the current state of practice in some of the selected sites, offered advantages strictly from a pedestrian's safety point of view (low speeds). Crosswalks located near the mid-block section, however, tended to be associated with reduced delay and pollutant emissions, a finding that applied to all eight study corridors. No relevant differences in the optimal crosswalk location were noted when a specific pollutant was considered in the optimization.

In spite of modeling different vehicle fleets across the three countries, the fleet effect on the optimal crosswalk locations was minimal (optimal solutions for US1 and SP1 sites included crosswalks located 10 to 15 m from the circulatory road).

The analysis of the relative crosswalk location for different values of spacing, confirmed the impact of spacing ($R^2 > 0.72$) on optimized crosswalk locations along mid-block section. Specifically, if the spacing is lower than 100 m, optimal crosswalk location is approximately in 20%-30% of the spacing length. Otherwise, if the spacing is between 140 and 200 m, crosswalk can be located at the midway position.

Notwithstanding the small improvements on delay, emissions or safety in the majority of the sites after the optimization procedure, this study contributed to the current literature in four aspects:

I. to assess the spacing between roundabouts as an influencing factor in determining the optimal crosswalk location;
II. to include local pollutant criteria to account location-specific environmental concerns;
III. to identify trade-offs between environmental /delay, and pedestrian safety fields;
IV. to supply basic design principles that help local authorities, transportation engineers, planners, and other professionals about pedestrian crosswalk location to accommodate location-specific needs and vulnerabilities.

Although this research provides measurement tools on how best to balance among competing objectives in locating the crosswalk, there are some limitations that must be highlighted. First, neither pedestrian delays nor illegal maneuvers (crossing outside the crosswalk) were considered in the analysis. The second limitation is that the relationship between optimal crosswalk location and operational variables such as arterial traffic and pedestrian flow was not fully addressed. The third limitation of this paper is the limited sample size of type of corridors (only conventional single-lane and multi-lane roundabouts were chosen in this case).

Therefore, future work is need, namely:

- To study other corridors with different roundabout layouts (e.g. turbo-roundabouts and urban mini-roundabouts) where pedestrian activity is high;
- To conduct a sensitivity analysis of the arterial traffic and pedestrian flow for each site in order to explore their impact on optimal crosswalk locations;
- To account and analyze the number of times that pedestrians cross outside crosswalks, especially in the situations in which crosswalks are far from roundabouts (mid-block section);
- To include above geometrical, operational and driving behavior outputs in the multi-objective optimization.

6.2.5. Acknowledgments

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6.3. Assessing the impact of spacing in closely-spaced intersections

PUBLISHED

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Abstract

Traffic lights or roundabouts along corridors are usually installed to address location-specific operational needs. An understanding of the impacts on traffic regarding to highly-congested closely-spaced intersections has not been fully addressed. Accordingly, consideration should be given to how these specific segments affect corridor performance as a whole.

One mixed roundabout/traffic light/stop-controlled intersections corridor was evaluated with the microscopic traffic model (VISSIM) and emissions methodology (Vehicle Specific Power – VSP). The analysis was focused on two major intersections of the corridor, a roundabout and a traffic light spaced lower than 170 m apart under different traffic demand levels. The traffic data and corridor geometry were coded into VISSIM and compared with an alternative scenario where the traffic light was replaced by a single-lane roundabout. This research also tested a method to improve corridor performance and emissions by examining the integrated effect of the spacing between these intersections on traffic delay and vehicular emissions (carbon dioxide, monoxide carbon, nitrogen oxides, and hydrocarbons). The Fast Non-Dominated Sorting Genetic Algorithm (NSGA-II) was used to find the optimal spacing for these intersections.

The analysis showed that the roundabout could achieve lower queue length (~64%) and emissions (16-27%, depending on the pollutant) than the traffic light. The results also suggested that 200 m of spacing using the best traffic control would provide a moderate advantage in traffic operations and emissions as compared with the existing spacing.

Keywords: Intersections, Multi-objective optimization, Micro-scale modeling, Spacing

6.3.1. Introduction and Research Objectives

Urban sprawl is known worldwide as the uncontrolled expansion of low-density and single-use suburban development. More than 25% of the European Union's territory has been directly affected by urban land use (64), and nearly 75% of Europeans live in urbanized areas (65). The impact from urban ways of living has increasingly more repercussions well beyond city boundaries. Thus, cities are the defining ecological phenomenon of the 21st century as they have become the major engine of economic development (66). Concurrently the phenomenon of urbanization is continuously eroding the countryside and making the boundary between cities and their suburban areas virtually undistinguishable.

A representative example of the above issues is found within urban arterials. Series of intersections along corridors are usually implemented according to the available space and do not follow any specific design criteria (67). Some of these traffic facilities are located in close proximity to each other (due to constraints in terms of land use), and the queue spillback from a downstream intersection can adversely affect the upstream throughput, and, as a result, the overall corridor performance.

Although research of the impacts on traffic performance and emissions of different traffic controls at isolated intersections and an arterial level has been conducted, little attention has been given to the real impacts on traffic regarding the short spacing between intersections. There is a concern that under specific traffic demands and intersection control (e.g. traffic light or roundabout) the impacts of specific segments of the corridor may be different by varying the spacing between intersections. In addition, the optimization of a particular pollutant (carbon dioxide – CO_2, carbon monoxide – CO, nitrogen oxides – NO_X and hydrocarbons – HC) could dictate different optimal spacing values.

The main contributions of this study to the current state-of-art are the following: *1*) Understanding the impact of highly-congested closely-spaced intersections within corridors; *2*) Implementing a multi-criteria analysis to assess the optimal spacing between intersections to improve corridor-specific operations; and *3*) Including specific pollutant criteria (global pollutants which have impacts on global warming; local pollutants which affect human health) to account corridor-specific environmental concerns.

One mixed roundabout/traffic light/stop-controlled intersections corridor is evaluated with the microscopic traffic model (VISSIM) and emissions methodology (Vehicle Specific Power – VSP). After that, a multi-objective genetic algorithm is used to search intersection-optimal spacing and the results compared with existing conditions. Thus, the objective of this paper is twofold:

- To compare the impacts of different closely-spaced traffic controls within a corridor on vehicle delay, and global (CO_2) and local (CO, NO_X and HC) pollutant emissions;
- To find the optimal spacing values for the intersections considering the best traffic control.

6.3.2. Literature Review

Spacing between intersections, both in terms of frequency and uniformity, governs the performance of urban and suburban roadways. Hence, the establishment of intersection spacing criteria for an arterial is one of the most important and basic access management techniques (68). There is no universally formal rule for the minimum spacing between adjacent intersections (69). As with standards for driveway spacing, the optimal spacing between signalized intersections depends on the speed, the traffic demand, and the intersection layout (70).

In North America and Europe, various design manuals propose threshold spacing values for signalized and unsignalized intersections. The National Cooperative Highway Research Program (NCHRP) Report 420 provides a range of optimum signal spacing values as a function of speed and cycle length for non-coordinated signals (68). For instance, intersections spaced at about 330 m from each other can provide progressive speeds up to 50 km/h at cycle lengths from 60 to 70 s. For cycle lengths higher than 100 s only spacing values above 600 m guarantee progressive speeds of 50 km/h. Gluck et al. (68) suggest that each additional signal over two per mile (400 m of spacing) increases travel time by 7%. The Transportation Research Board Access Management Manual recommends that spacing between major urban arterials should be equal or higher than 800 m considering an Average Annual Daily Traffic (AADT) between 2,000 and 15,000 vehicles (71). Whereas, French guidelines state that a minimum spacing of 250 m can be adopted whether site characteristics have conditions to make this feasible (69). The Colorado Access Demonstration Project found that 800 m of spacing can reduce vehicle-hours of delay and travel by 60% and 50%, respectively, compared with signals spaced at 400 m with full median openings (71).

According to the arterial segment running time formula in the Highway Capacity Manual (HCM), time spent at arterials increases as average spacing increases. However, HCM method does not take account for the effect of queue spillback from a downstream signal (6). Synchronization of adjacent traffic lights (green waves) helps to reduce vehicle stops and delay. The Federal Highway Administration (FHWA) suggests that spacing shorter than 300 m is difficult to coordinate on arterials which have the same signal controller (72). Tarko et al. (73) explain that good coordination for conventional signalized intersections with protected turn bays is only attained for equally spaced intersections in both directions of traveling.

The current research on emissions and fuel consumption at different corridors with traffic lights (45, 74-76) and mixed traffic lights/roundabouts corridors (18, 77, 78) is extensive, but does not explore the influence of spacing on traffic operations. Several studies have been performed to assess roundabout corridors performance in terms of capacity and emissions (1, 19, 41, 42, 49). In particular, Fernandes et al. (41) demonstrated that spacing between roundabouts had an impact on the spatial distribution of CO_2 emissions (R^2>0.50), especially in the case of closely-spaced roundabouts (<170 m). However, the above-mentioned research did not include an in-depth assessment of the spacing on traffic operations. Concurrently, additional relevant research on environmental impacts in conventional (14, 79-81) and innovative (82, 83) roundabouts did not address the impacts of nearby upstream and downstream intersections.

One of the main conclusions gained from the literature review is the realization that there is a higher need for systematic analysis on the impact that specific segments of a corridor with high traffic flows have on overall corridor performance. Furthermore, little is known about the effect that spacing could have on traffic performance and emissions. Lastly, a proper selection to gain optimal spacing between intersections to improve simultaneously traffic performance and emissions should also be explored.

The novel purpose of this research is to evaluate a specific segment of a corridor to provide some evidences about what the causes of its impacts might be. After that, several methods to improve the performance and emissions of the overall corridor are investigated, namely: *1*) replacement of the existing traffic control; and *2*) placement of such intersection (within feasible distances) along the mid-block section. Finally, this research tests and verifies these methods in a real world urban corridor. The effects of spacing distances were hypothesized to be different for each pollutant and concomitantly lead to a trade-off analysis among the selected variables, namely:

- Low spacing between intersections along an arterial will have a negative impact on CO_2 emissions and traffic performance and at the same time can have a different effect on local pollutants, since vehicles have a very short distance to attain high speeds;
- High spacing could reduce delay and CO_2 emissions, but may be diverse in local pollutants, because vehicles attain high speeds at mid-block area, and they could experience high acceleration-deceleration rates at the downstream and upstream areas of either intersection.

6.3.3. Methodology

The core idea of the proposed methodology was to introduce a microsimulation framework to assess traffic performance and emissions of an existing corridor as well as to implement future operational scenarios. The methodology is explained in five steps (**Figure 6.13**). First, data were collected in the selected baseline site. Second, the network was coded, latter calibrated, and validated for the baseline site using the microsimulation platform of traffic and emissions. Third, different operational scenarios were defined and compared. Fourth, emissions were estimated using VSP. Step five was focused on the optimization of the results using a multi-objective analysis.

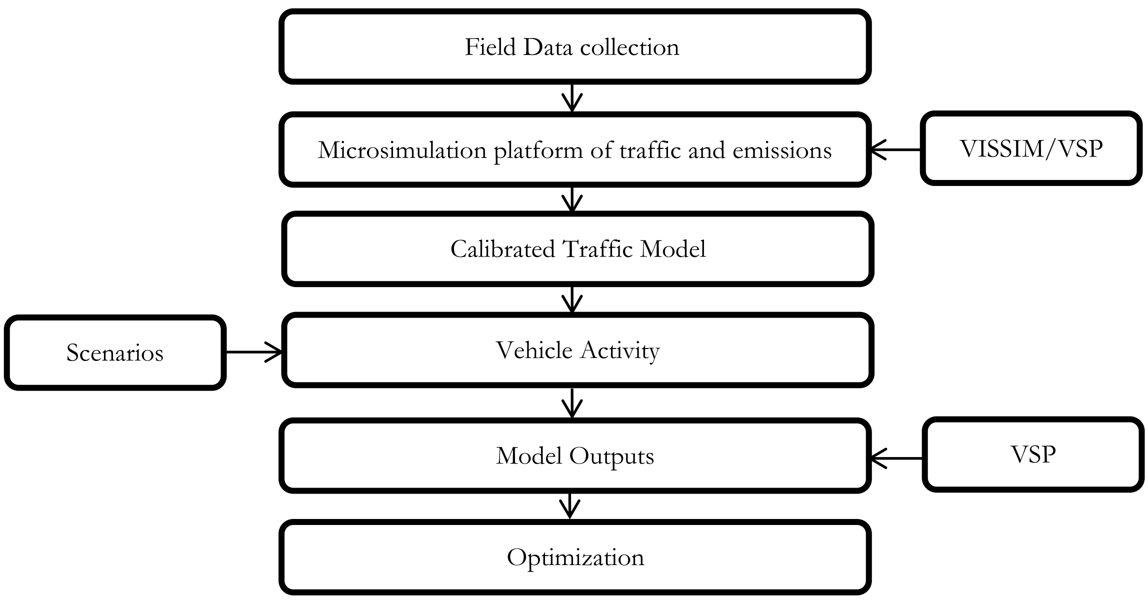


Figure 6.13 Summary of methodological steps.

6.3.3.1. Microsimulation platform of traffic and emissions

Traffic Modeling

VISSIM (German acronym for *Verkehr In Städten SIMulationsmodell*) microsimulation model is recognized as a powerful tool for corridors with different forms of intersections in order to perform reliable operational assessment, namely: *a*) to define different parameters of driving behavior for roundabouts and traffic lights as car-following models or gap-acceptance (22); *b*) to simulate fixed-cycle signal controls (22); *c*) to calibrate and validate a wide range of parameters to set faithful representations of the traffic on an arterial level for capacity and emissions' purposes, as demonstrated elsewhere (18, 42, 84); and *d*) to enable storing and exporting vehicle dynamics data at high time resolutions that can be used by external emissions models.

Emission Modeling

Vehicular emissions were estimated using VSP methodology (24) for four main reasons: *1*) it allows estimating instantaneous emissions based on second-by-second vehicle activity data, taking the trajectory files given by VISSIM; *2*) it has been shown as an useful explanatory variable for estimating variability in emissions (56); *3*) it includes the impact of different levels of accelerations and speed changes on emissions estimates (55); and *4*) it includes a wide range of engine displacement values, and therefore be applied to the European car fleet composition.

VSP is a function of instantaneous speed, acceleration-deceleration, and road grade (24). The VSP values are categorized in 14 modes, and an emission factor for each mode is used to estimate CO_2, CO, NO_X and HC emissions from Passenger Vehicles (25, 26) and Light Diesel Duty Trucks (LDDT) (26). Previous study has documented the effectiveness of the VSP approach with the VISSIM traffic model in analyzing emission impacts of arterials with different forms of intersections (42). **Eq. 6.6** provides the VSP calculation for a passenger vehicle (24):

$$VSP = v.\left[1.1.a + 9.81.\sin\left(\arctan\left(grade\right)\right) + 0.132\right] + 0.000302.v^3 \qquad \textbf{Eq. 6.6}$$

where VSP is the Vehicle Specific Power (kW/ton), v is the vehicle instantaneous speed (m/s), a is the vehicle instantaneous acceleration or deceleration (m/s^2) and the grade is Terrain gradient (decimal fraction).

These terms represent the engine power required in terms of kinetic energy, road grade, friction and aerodynamic drag. The average emission rates for pollutants CO_2, CO, NOx and HC by VSP mode and vehicle type are reported in the following studies: Gasoline Passenger Vehicles (GPV) (25), and Diesel Passenger Vehicles (DPV) and LDDT (26). A console application in C# was mobilized to compute second-by-second vehicle dynamics from VISSIM output for emissions estimate in VSP.

Traffic Model Calibration and Validation

Model evaluation of the baseline site was made in two main steps: calibration and validation. In the first stage, the VISSIM traffic model was calibrated to reproduce performance measures such as traffic flows, speed, and queue lengths observed in the field. Thus, driver behavior parameters of the VISSIM traffic model were adjusted to assess their impact on traffic volumes and speed for each coded link. The calibrated driver behavior measures included the average standstill distance, additive and multiple parts safety distance (car-following), minimum gap time and headway distance (gap acceptance), and simulation resolution (22). More details about this calibration procedure can be found in Fernandes et al. (50).

In the second stage, the model was validated by comparing the estimated and observed traffic flows, travel time, average acceleration (which has a high impact on emission levels), and cumulative VSP modes distributions with a preliminary number of simulation runs.

Traffic flows and travel time were validated using Geoffrey E. Havers (GEH) statistic (31) while Mean Absolute Percent Error (MAPE) was used to measure the differences between the observed and the estimated accelerations. To examine the consistency between the estimated and observed VSP mode distributions, the two-sample Kolmogorov-Sminorv test (K-S test) for a 99% confidence level was employed, as explained elsewhere (50, 85).

Approximately 70% of the data collected were used for calibration, and the remaining data for validation.

6.3.3.2. Model Development

Baseline Site

Portugal has experienced some of the most rapid increases in urban development in the EU [urban population rose from 48% to 63% (65) between 1990 and 2014]. This increase has been mostly focused around the metropolitan areas of Lisbon and Porto, and along some medium-sized cities. In the majority of the cities North of Portugal, new houses have been built by land owners, contributing to a more scattered urban pattern, and compromising the feasibility of planning new developments because of the irregular spatial growth.

Thus, an urban mixed corridor with roundabouts/traffic lights/stop-controlled intersections exhibiting high traffic was sought out for this research (**Figure 6.14**). The case study is located near the city of Guimarães (North of Portugal), a European medium-sized city with 158,124 inhabitants with a population density of 656 inhabitants/km^2 (21).

The posted speed limit is 50 km/h and the corridor has one lane in each direction throughout its length. The spacing is not uniform between intersections (the coefficient of variation of average spacing is 0.58). The corridor is approximately 1,500 m long, and it includes three single-lane roundabouts (I1/I2/I6), one traffic light intersection (I3), and two two-way stop controlled intersections (I4/I5). I3 has a fixed-cycle with the same setup during the day (overall cycle time is 107 s) and does not include any left-turn and right-turn lanes on entry legs. As noted, I2 and I3 are located in close proximity to each other (spacing of 167 m). **Table 6.9** presents the information regarding the site's characteristics.

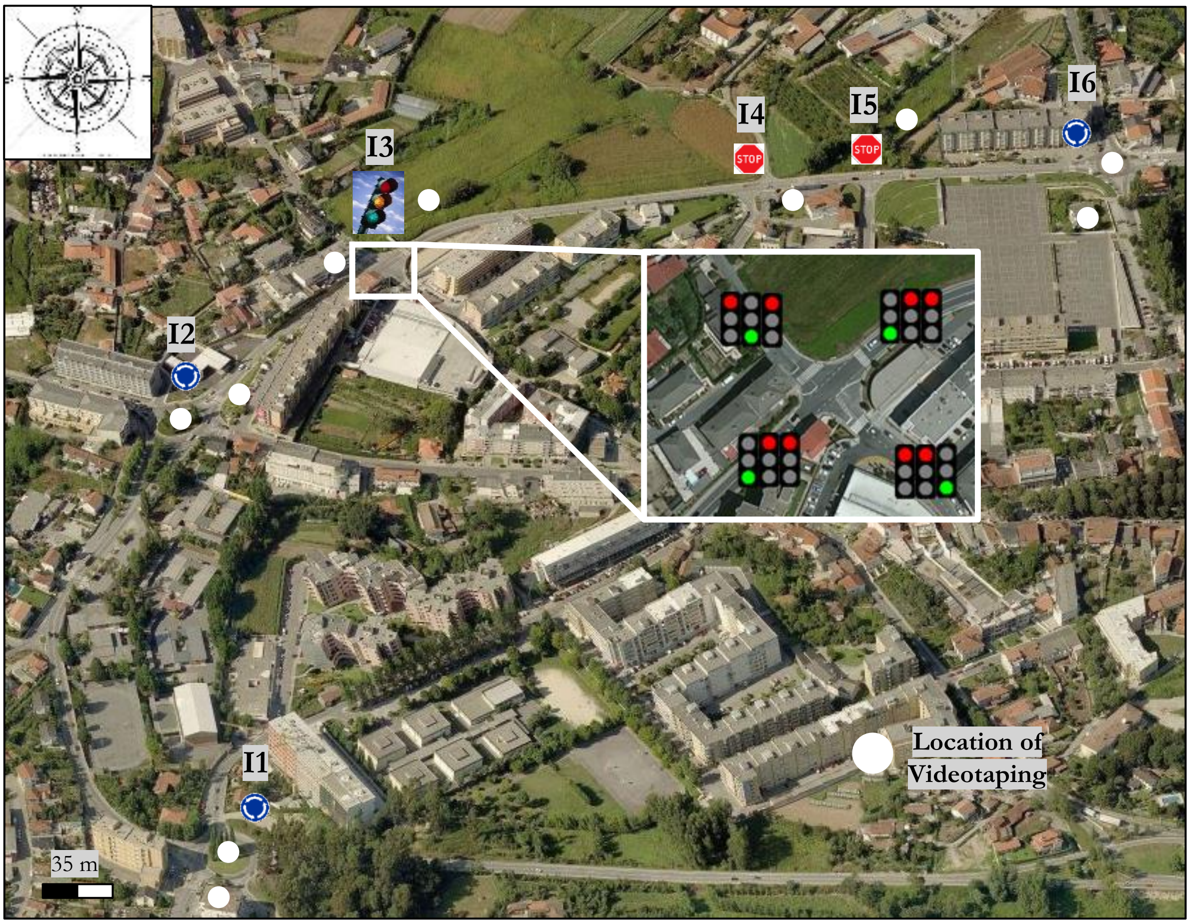


Figure 6.14 Aerial view of the selected corridor with the intersections' identification (I1, I2, I3 – including phasing, I4, I5 and I6) (Guimarães, Portugal). Source: https://www.bing.com/maps/

Table 6.9 Summary of the site characteristics

Intersection ID	Type	GPS coordinates	# approach lanes	# legs	Distance to downstream analysis intersection [m]	Average Spacing [m]
I1	Single-lane Roundabout	41°28'58.62"N 8°21'7.92"W	1	5	453	223.4
I2	Single-lane Roundabout	41°29'11.09"N 8°21'9.17"W	2	4	167	
I3	Traffic Light	41°29'15.75"N 8°21'3.68"W	1	4	253	
I4	Stop-Controlled	41°29'18.18"N 8°20'53.20"W	1	3	70	
I5	Stop-Controlled	41°29'18.56"N 8°20'50.23"W	1	3	174	
I6	Single-lane Roundabout	41°29'19.12"N 8°20'43.75"W	1	4	-	

Field Data Collection

During typical weekdays, traffic counts suggest that the evening peak period occurs between 5:30-7:00 p.m. Thus, the following data were collected at the selected corridor during that time in November and December 2014:

- Traffic flow (Light Passenger Vehicles – LPV, transit buses and Heavy Duty Vehicles – HDV);
- Time-Dependent Origin-Destination (O-D) matrices;
- Traffic lights timing (cycle length and phasing);
- Gap-acceptance and gap-rejection data;
- Queue lengths;
- High-resolution vehicle activity data (speed, acceleration-deceleration and grade).

Traffic flows, queue lengths, and traffic lights timing were collected from overhead videos installed at strategic points along the corridor, as illustrated in **Figure 6.14**. Apart from the I4 and I5 intersections, all entries were observed at each intersection to obtain the maximum queue length (for further information, please consult **Table 6.12**). The selection criterion was the existence of periods of continuous queuing on those locations. Traffic flows were recorded over 12 different typical weekdays (Tuesday and Wednesday) under dry weather conditions. Later, in the transportation laboratory, the traffic data for each vehicle class were compiled to define O-D tables based on trips along the whole corridor.

The vehicle activity data characterization was recorded using two LPVs with engine size lower than 1.4l (Euro III and Euro V Emission Standards) equipped with Global Positional System (GPS) travel record and On-Board Diagnostic (OBD), making several turning movements at the corridor (I1→I6 and I6→I1 directions, as displayed in **Figure 6.14**). It should be emphasized that the specifications of these vehicles are within the emissions' factors of the emission model. Additionally, the test-vehicles are very representative of the LPV category in Europe (86).

90 GPS travel runs for each through movement were performed for this study (approximately 150 km of road coverage over the course of 6 h). To reduce systematic errors, 4 different drivers (three males and one female, ages 24 to 33 with varying levels of driving experience) performed an identical number of trips (approximately 18) on each monitoring driving route. The above series of measurements were sufficient to enable the estimation of a 95% confidence interval in relation to the average and standard deviation of the measured parameters (51).

Modeling corridor in VISSIM

The simulation model was run for 75 min (5:45-7:00 p.m.) with the first 15 min used as a warm-up period, and data extracted only for the remaining 60 min. Since transit buses and heavy-duty vehicles represented less than 1% of traffic composition, they were excluded from this analysis. Five O-D matrixes of 15 minutes for LPV were generated for the period between 5:45 p.m. and 7:00 p.m., and further imported in VISSIM. Traffic flows were assigned to respective route by applying Dynamic Traffic Assignment (DTA) (22). The modeling of yield areas at roundabouts was made using the Priority Rules tool of the VISSIM model (22), and assuming the same minimum gap time and headway distance in each one of the yield areas. The coded network is exhibited in **Figure 6.15**.

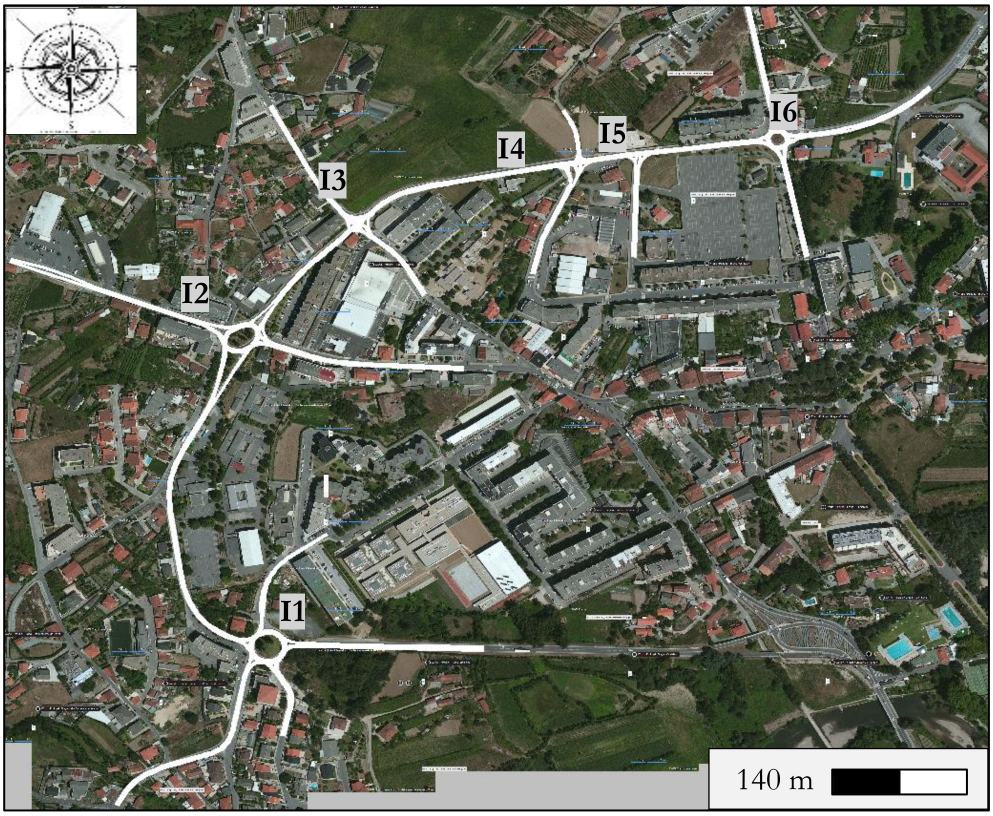


Figure 6.15 Coded network in VISSIM. Source: https://maps.google.com/

6.3.4. Results and Discussion

6.3.4.1. Model Calibration and Validation

Using the initial default values, R^2 values of 0.98 and 0.61 were obtained from linear regression models between the estimated speeds and traffic flows, respectively, against field data, as displayed in **Figure 6.16**-a. After the calibration, (**Figure 6.16**-b) the results demonstrated large improvements in speed values. The R^2 values for traffic flows and speed were higher than 0.80, indicating that the simulated data explained more than 80% variation in the observed data.

Table 6.10 presents the calibration and validation results for the traffic model and the corresponding statistic test. Since a fixed value was needed to setup the time resolution of traffic model and emission methodology (second-by-second), a constant value of 10 time steps per simulation seconds for simulation resolution parameter was used. After the calibration, all the links achieved a GEH less than 4, which fulfilled the calibration criteria (31). The calibration results for calibrated gap time at roundabouts also reflected local driving habits (63). Regarding the validation results, the comparison of observed and estimated flows and travel time was conducted using 15 random seed runs (32), which demonstrated that 86% of the coded links attained GEH values below 4 (31).

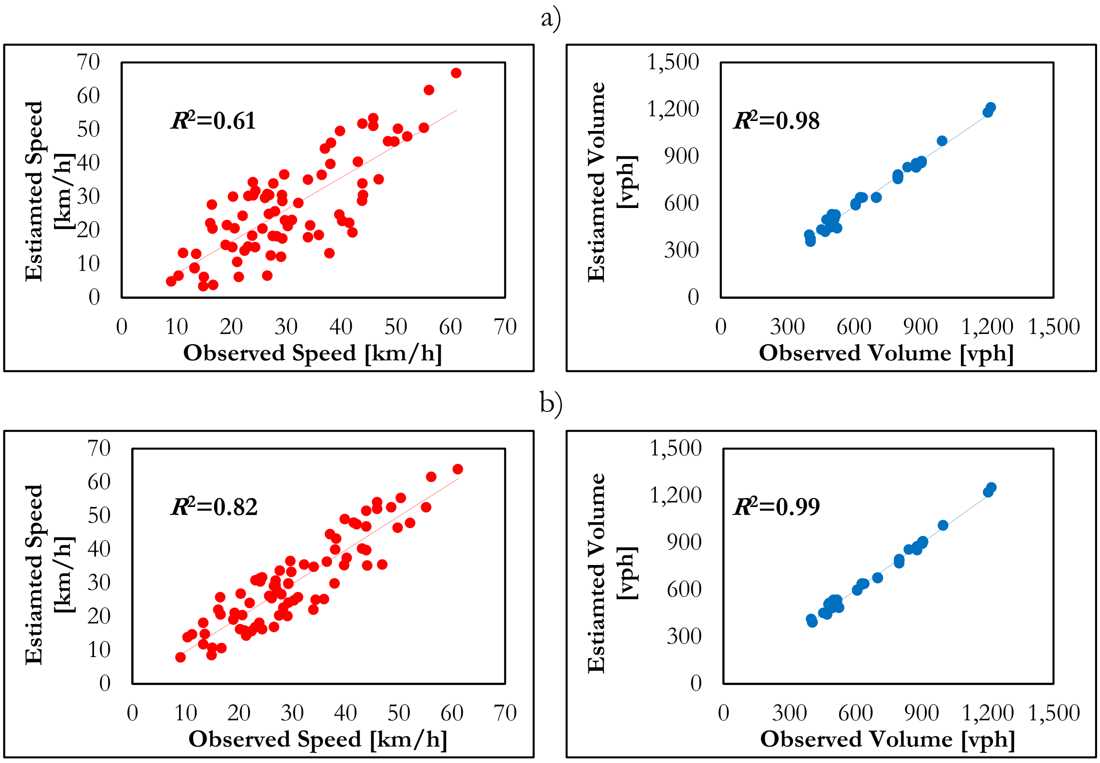


Figure 6.16 Observed versus Estimated speed and traffic flows: a) Default parameters; b) Calibrated model.

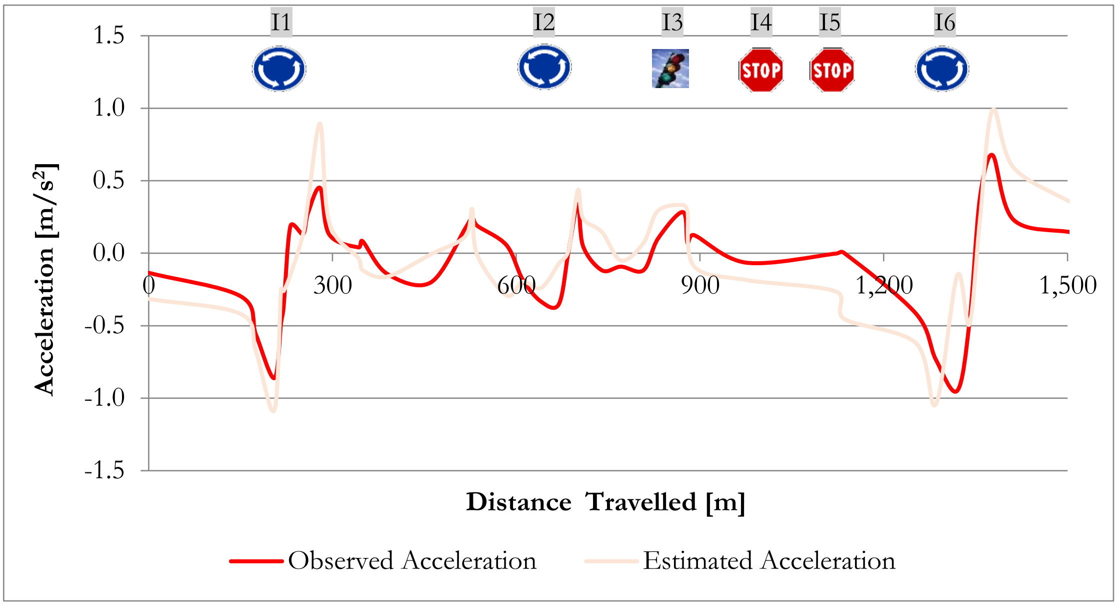
Table 6.10 Summary of calibration and validation of traffic model

Model	Parameter	Value	NRMS	GEH	Queue length
Default	Average standstill distance (m)	2.0	0.881	< 4 for 88 % of the cases	22% higher than field data (*p*-value = 0.53)
	Additive part of safety distance	2.0			
	Multiple part of safety distance	3.0			
	Minimal gap time (s)	3.0			
Calibrated	Average standstill distance (m)	1.97	0.609	< 4 for 100 % of the cases	9% lower than field data (*p*-value = 0.75)
	Additive part of safety distance	1.95			
	Multiple part of safety distance	2.9			
	Minimal gap time (s)	3.1			
Validated	Average standstill distance (m)	1.97	0.730	< 4 for 86 % of the cases	18% lower than field data (*p*-value = 0.75)
	Additive part of safety distance	1.95			
	Multiple part of safety distance	2.9			
	Minimal gap time (s)	3.1			

Legend: *NRMS: Normalized Root Mean Square*

Figure 6.17 a-b exhibits the observed and estimated average acceleration profiles along the corridor for monitoring routes. The graphs confirmed that estimated acceleration values were slightly higher than observed data at the downstream intersections, which is in accordance with previous studies (87). Despite these differences, MAPE values did not exceed 20% in both routes, which suggested that the VISSIM calibrated parameters provided reasonable estimates for the studied corridor. Because vehicles were subject to continuous stop-and-go situations between downstream of I3 and upstream of I2, high variations of the acceleration curves were observed after I3 for I6-I1 route (**Figure 6.17**-b).

a)



b)

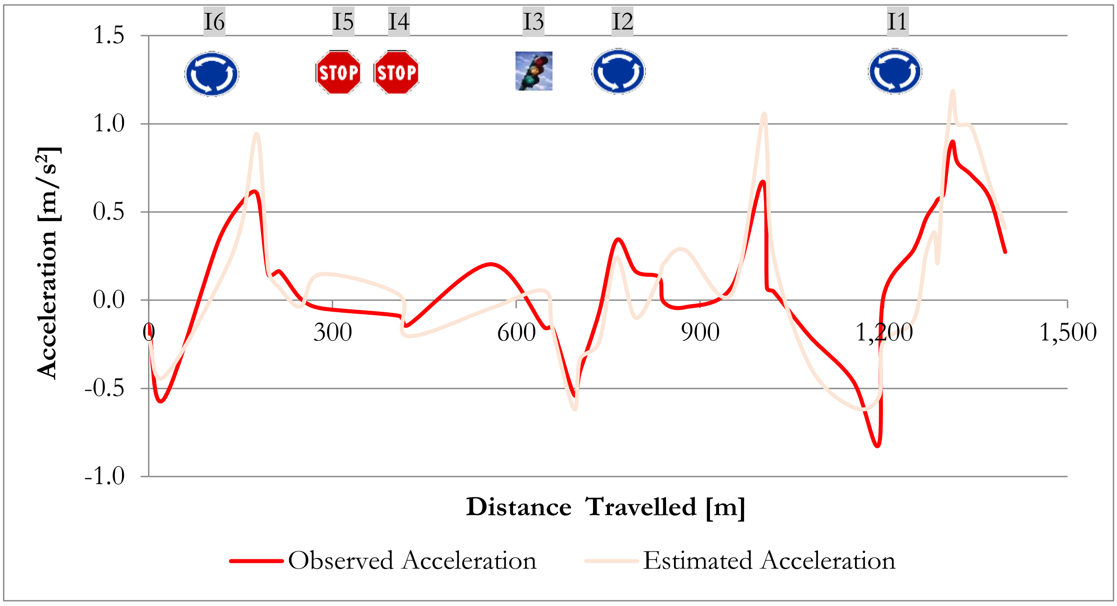


Figure 6.17 Observed and Estimated accelerations distributions along the corridor: a) I1-I6 route; b) I6-I1 route.

The assessment of VSP modes in terms of cumulative distributions revealed that two results from the observed and estimated data of the monitoring routes followed an identical trend. In such cases, and as presented in **Table 6.11**, *D*-values for I1-I6 and I6-I1 routes with a 99% confidence level were 0.059 (*D*-critical = 0.060) and 0.056 (*D*-critical = 0.061), respectively. Still, the findings showed small differences between travel time data samples (*p*-value >0.05). To conduct the above comparison approximately 15 data samples for each route were used.

Table 6.11 Summary of validation of traffic model for the monitoring routes

Movement	Parameter	Observed	Estimated	Result
I1→I6	VSP Modes	–	–	*D*-value = 0.059
	Travel Time (s)	289 ± 87	285 ± 67	*p*-value = 0.94
I6→I1	VSP Modes	–	–	*D*-value = 0.056
	Travel Time (s)	275 ± 57	256 ± 39	*p*-value = 0.53

Note: *Validated model with 15 random seed runs*

6.3.4.2. Traffic performance

Table 6.12 summarizes the simulated values of traffic flow on each approach intersection road during the one-hour evening peak (6:00-7:00 p.m.). The level of service (LOS) criteria, the queue distance and the volume-to-capacity ratio (v/c) for each lane are provided, as well as LOS criteria and stops per vehicle for the intersection (6).

The average number of vehicles entering each intersection ranged from 1,060 to 2,590 vehicles per hour (vph) for I5 and I2, respectively.

Several conclusions about the effect of each intersection of the corridor can be drawn. First, I2 and I3 operate with poor levels of service, respectively, LOS E (control delay between 35 and 50 s/vehicle) and LOS D (control delay between 35 and 55 s/vehicle) (6). Second, the east entry of I2 and west entry of I3 reach queue distances exceeding 200 m, which is longer than the available spacing between I2 and I3 (167 m).

In the eastbound route of I2, the queue exceeds 400 m (almost the distance between the upstream of I3 and the downstream of I6, as presented in **Table 6.9**). This means that more than 50% of vehicles enter I2 from the east entry leg (~700 vph) are retained at the upstream of I3 (caused by red signal). Simultaneously, the through traffic (east-west and west-east) must wait for left-turn vehicles since there are not left-turn lanes at I3.

The analysis of the corridor suggests that the main congestion focus is found at I3 influence area. Moreover, the short distance to the I2 paired with high traffic flows and an inefficient traffic control strategy, as is the case of I3, negatively affected overall corridor performance. Replacing the current traffic control at I3 could be a solution to mitigate the traffic congestion for the studied corridor.

Table 6.12 Traffic performance results of the selected corridor

ID	North Approach				South Approach				West Approach				East Approach				Average LOS	Stops per veh
	Traffic flow [vph]	LOS	Queue (m)	v/c ratio	Traffic flow [vph]	LOS	Queue (m)	v/c ratio	Traffic flow [vph]	LOS	Queue (m)	v/c ratio	Traffic flow [vph]	LOS	Queue (m)	v/c ratio		
I1	276	D	65	0.70	654	F	251	1.03	797	C	175	0.92	640	C	92	0.76	C	1.33
I2	684	C	134	0.86	291	C	49	0.60	904	F	291	1.10	703	F	440	1.21	E	1.88
I3	114	E	56	0.47	348	E	108	0.73	491	D	203	0.57	526	D	212	0.75	D	0.86
I4	21	C	3	0.09	21	C	3	0.07	509	A	24	0.27	513	A	24	0.28	C	0.06
I5	-	-	-	-	48	C	11	0.14	514	A	0	0.28	495	A	24	0.27	D	0.13
I6	256	B	29	0.45	251	B	21	0.36	403	B	37	0.52	606	B	68	0.68	B	0.83

Note: ** The southwest approach of I1 was excluded (traffic flows < 20 vph); ** Based on preliminary traffic analysis with assignment of the overall corridor*

Shadow cells indicate LOS F

6.3.4.3. Operational Scenarios

With these concerns in mind, several scenarios were established to improve traffic performance and reduce vehicular emissions along the case study corridor. Initial evaluation performed in the simulation demonstrated that 130% of the traffic demand induced traffic congestion in the modelling network (several vehicles were retained in the centroids at the end of the simulation period).

The Baseline Scenario is the calibrated simulation model with the existing control at the I3 intersection. Next, a single-lane roundabout layout (inscribed circle diameter = 33 m, circulating lane width = 5.6 m) replaced the traffic light (**Figure 6.18**). The roundabout layout was designed according the Portuguese design guidelines (88). The latter two scenarios were analyzed and compared considering two main demand levels (**Table 6.13**): *1*) observed traffic flows (100% demand factor) and *2*) expected traffic growth of 25% (125% demand factor).

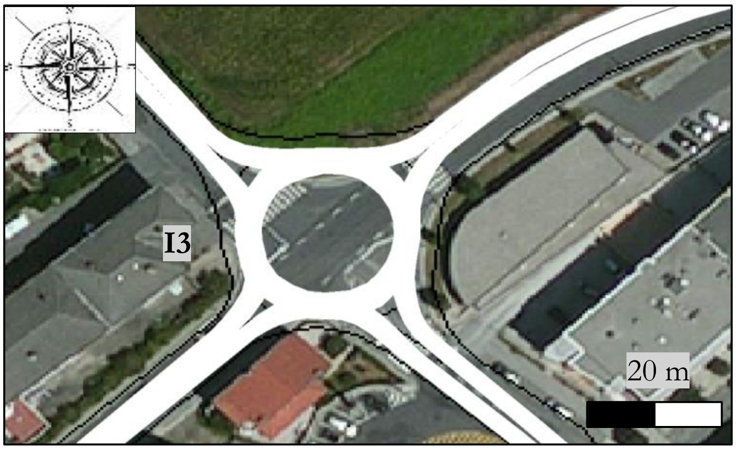


Figure 6.18 Proposed single-lane roundabout layout at I3 intersection. Source: https://maps.google.com/

Table 6.13 Scenario description

Scenario	Traffic Control at I3 intersection	Demand Level
Baseline	Traffic Light	100%
		125%
Scenario 1	Single-lane Roundabout	100%
		125%

For each scenario, a fixed time signal control method was used at I3 together with the phase sequence exhibited in **Figure 6.14**. The cycle time and phase timing were optimized using aaSIDRA model (89) as follows:

- 100% demand: east and west – 27 s; north – 12 s; south – 19 s (cycle length of 85 s);
- 125% demand: east and west – 30 s; north – 12 s; south – 21 s (cycle length of 90 s).

Total emissions were calculated considering the following distribution: 44% of GPV with engine size <1.2l; 35% of DPV<1.6l; and 21% of LDDT <2.5l (23). Because the terrain was flat (slope <1%), the effect of the grade was ignored.

6.3.4.4. Traffic performance measures and emission rates

This section compares emissions and traffic performance parameters of the two scenarios to the baseline scenario and two demand levels (100% and 125%). The performance measures and vehicle activity data speed and acceleration-deceleration on a second-by-second basis (to be computed in the VSP methodology) were given from the vehicle record evaluation of the VISSIM model (22).

The emissions and traffic performance results are presented in **Table 6.14** by scenario and demand level to the evening peak period (6:00-7:00 p.m.). Key observations from the data in **Table 6.14** are:

- When the 100% demand factor level was considered, Scenario 1 was the best design solution for I3 intersection. It had average emissions reductions of about 6%, while the average delay and number of stops decreased by more than 22%;
- For the 125% demand factor scenario, the difference in the amount of emissions between traffic light and single-lane roundabout increased, when compared with the observed demand levels. Scenario 1 yielded the highest emissions reductions in CO_2 and HC with 24% and 27%, respectively. Alongside of each other, it was very effective in terms of traffic performance measures (its implementation allowed the total number of stops and average delay to be reduced by 60% and 44%, respectively);
- The average queue length on the entry legs of I2 and I3 decreased at Scenario 1 when compared to the Baseline Scenario (57% and 64% short queues in 100% and 125% demand levels, respectively).

Table 6.14 Variation of emissions and traffic performance parameters per location in relation to the baseline scenario

Demand Level	Scenario	Emissions				Traffic Performance		
		CO_2 [kg]	CO [g]	NO_X [g]	HC [g]	Delay [s/veh]	Total stops	Queue length[a] [m]
100%	**Baseline**	903	1,291	2,767	48	50.19	5,869	154
	Scenario 1	848 (-6%)	1,222 (-5%)	2,584 (-7%)	46 (-5%)	38.05 (-24%)	4,542 (-23%)	66 (-57%)
125%	**Baseline**	1,363	1,698	4,016	81	103.67	18,804	325
	Scenario 1	1,033 (-24%)	1,432 (-16%)	3,199 (-20%)	59 (-27%)	58.16 (-44%)	7,611 (-60%)	116 (-64%)

Note: [a]*Average queue length at the I2/I3 entry legs*

Another reason for increasing capacity after roundabout implementation may be due to the number of approaching vehicles at I2 and I3 (**Table 6.15**), especially under high demand levels. With 125% demand factor, the number of approaching vehicles at the I2 and I3 with baseline conditions was lower (-10%) than those obtained in the Scenario 1. This meant that I3 did not completely flow all traffic (even considering a longer green time along major arterials) that crossed the intersection. Accordingly, some vehicles no longer enter or leave other intersections, and further they are retained in the centroids. **Table 6.15** also lists LOS criteria for the intersection. As suspected, LOS criteria at I2 and I3 improved after roundabout implementation. For instance, I2 operated with LOS C in both demand periods, which was not happened in the baseline (LOS E and LOC F for 100% and 125% demand factors, respectively).

It is worth noting that simulated left-turning vehicles delayed right-turning and through traffic behind them while waiting for a gap from opposing traffic at the I3 baseline. This phenomenon does not occur in the reality since some vehicles in the queue attempts to overtake the left-turning traffic if they have space on the road. However, left turning movements only represented 6% and 9% of westbound and eastbound approach traffic, respectively, at the I3.

Table 6.15 Number of approaching vehicles and LOS at the I2 and I3

Scenario	Demand level	ID	Approach Traffic [vph]	Average LOS
Baseline	**100%**	I2	2,505	E
		I3	1,403	D
	125%	I2	2,241	F
		I3	1,268	F
Scenario 1	**100%**	I2	2,507	C
		I3	1,407	A
	125%	I2	2,712	C
		I3	1,806	C

In summary, the comparison of the corridor's layout dictated large improvements when a single-lane roundabout replaced the existing traffic light. This was particularly perceptible in the queue length, which was reduced by more than half (upstream vehicles do not always perform complete stops at roundabouts).

Despite the improvements, the average queue length is still high (>65 m) in Scenario 1, especially in a future traffic increase situation (125% demand factor). This presumably suggests that the spacing between I2 and I3 intersections may impact on the traffic operations along the corridor. This subject is addressed in the following section.

6.3.4.5. Multi-objective optimization

Considering the foregoing discussion, several spacing values were tested to find a set of optimal spacing locations between I2 and I3 that allowed minimizing delay and vehicular emissions. Scenario 1 with 100% and 125% demand levels was then applied, assuming several spacing lengths (S) ranging from 70 m to 250 m in 10-m increments relatively to the I2 exit section. For these two demand levels, the roundabout I3 was moved along the mid-block section within feasible values (according to the geometry layout of the corridor). It should be noted that the distance to downstream intersection (I4) is only 253 m, as described in **Table 6.9**.

The following objective variables were optimized: 1) delay versus CO_2; 2) delay versus CO; 3) delay versus NO_X and 4) delay versus HC. Several regression models were tested to fit each variable against the decision variable (S). A set of 10 optimal spacing solutions was used in this research.

As a solution for the proposed problem, a genetic algorithm (GA) was selected. GAs are heuristic search techniques based on the evolutionary ideas of natural selection and genetics (90). The Fast Non-Dominated Sorting Genetic Algorithm (NSGA-II) proposed by Deb et al. (33) was used. NSGA-II proceed in four main steps.

First, the population (optimal spacing length values) was initialized taken into account the objective variables (delay, CO, CO_2, NO_X or HC) range and spacing constraints (distance in relation to the downstream I4).

Second, the population was sorted based on a non-domination criteria (a feasible solution is non-dominated whether does not exist another feasible solution better than the actual one as a delay value without worsening CO, CO_2, NO_X or HC values). NSGA-II uses a binary tournament selection based on the rank and crowding distance process for choosing the parents from the population. An individual (S value) is selected in the rank if is smaller than the other individual or if crowding distance is greater than the other. The crowding distance measures how close an individual is to its neighbors. The diversity in the final optimal spacing solutions is better as the crowding distance is larger.

In the third step, the selected population generated offspring by applying crossover and mutation rates, and then parents and offspring merged to select the best individuals in the population. This allows preserving individuals from one generation to another (elitism).

Four, the procedure stopped after reaching stopping criteria (number of generations/iterations), and the optimal solutions found in the Pareto Approximate Front (POF). Deb et al. (33) details the overview of NSGA-II.

To ensure the diversity in the solutions and the convergence to Pareto Optimal Front (POF) (34), a sensitivity analysis was conducted. First, the maximum number of iterations (stopping criteria) was set to 2,000 for all the test instances, while the crossover and mutation rates were set at 90% and 10%, respectively. Second, each scenario was run 15 times in the NSGA-II code. In doing so, the indicators measured the diversity of the solutions [Spread and Uniformity Measure metrics (35)] and the convergence to POF (number of dominated solutions) were computed and analyzed. Once guaranteed the above objectives (diversity and convergence) in all scenarios, an equal maximum number of generations was used.

The analysis of the diversity in the solutions and convergence to POF dictated that a maximum of 500 iterations was sufficient to reach convergence. After testing several crossover and mutation rates, a slight variation of the final POF was observed on each of the multi-objective runs. Thus, crossover and mutation rates were set at 95% and 5%, respectively.

Figure 6.19 depicts the final Pareto front from the final populations obtained for Scenario 1 and the average corridor v/c ratio. For each demand level, a 2-D scatter plot with two objective functions – emissions (x-axis), and average delay (y-axis) – is illustrated. Each data label is a Pareto point that represents an optimal spacing (S) solution of the final POF (its correspondent value is presented in **Table 6.16**). The optimal spacing solutions, which conducted with the minimal vehicular emissions, were allocated furthers to the upper-left, while the optimal spacing solutions, which led to the minimal average delay, was assigned lower-right. A trade-off occurs along the graph of the optimal spacing solutions.

For the 100% demand factor level (**Figure 6.19** a-d), the findings confirmed that low-spacing values (<180 m) and high-spacing values (>222 m) were not good options. Furthermore, no significant differences in the optimal spacing set among pollutants were observed. For solution 5 (data label point which is closest to the abscissa of the graph), that is, 207 m of spacing, average delay and CO_2 emissions decreased by 5% and 2%, respectively, when compared to the existing spacing. For a chosen value of the lowest optimal spacing value (solution 1), reductions of 3%, 2%, 4% and 6% in CO_2, CO, NO_X and HC, respectively, can be expected on case study corridor in relation to 167 m of spacing (see **Table 6.14** for those details).

Concerning the highest demand level (125%), the final Pareto front for all pollutants pointed out that high-spacing (>220 m) must be avoided by transportation planners to implement at the case study corridor (**Figure 6.19** e-h). For instance, if one adopted solution 6 (intermediate solution), then one could save up to 3%, 7% and 8% in CO, NO_X and HC, respectively. Alternatively, a decision-maker can use a spacing solution of 200 m, and reduce the average amount of emissions and delay in more than 5% and 6%, respectively, if the spacing was 167 m (actual location). However, the set of final POF varied for some pollutants. Specifically, optimal spacing values for CO_2 ranged from 199 m and 203 m, while local pollutants accepted spacing values close to the actual spacing distance (~180 m). This is mostly because of the high acceleration-deceleration rates that vehicles experience as they approach each intersection, and the result is especially relevant for CO emissions.

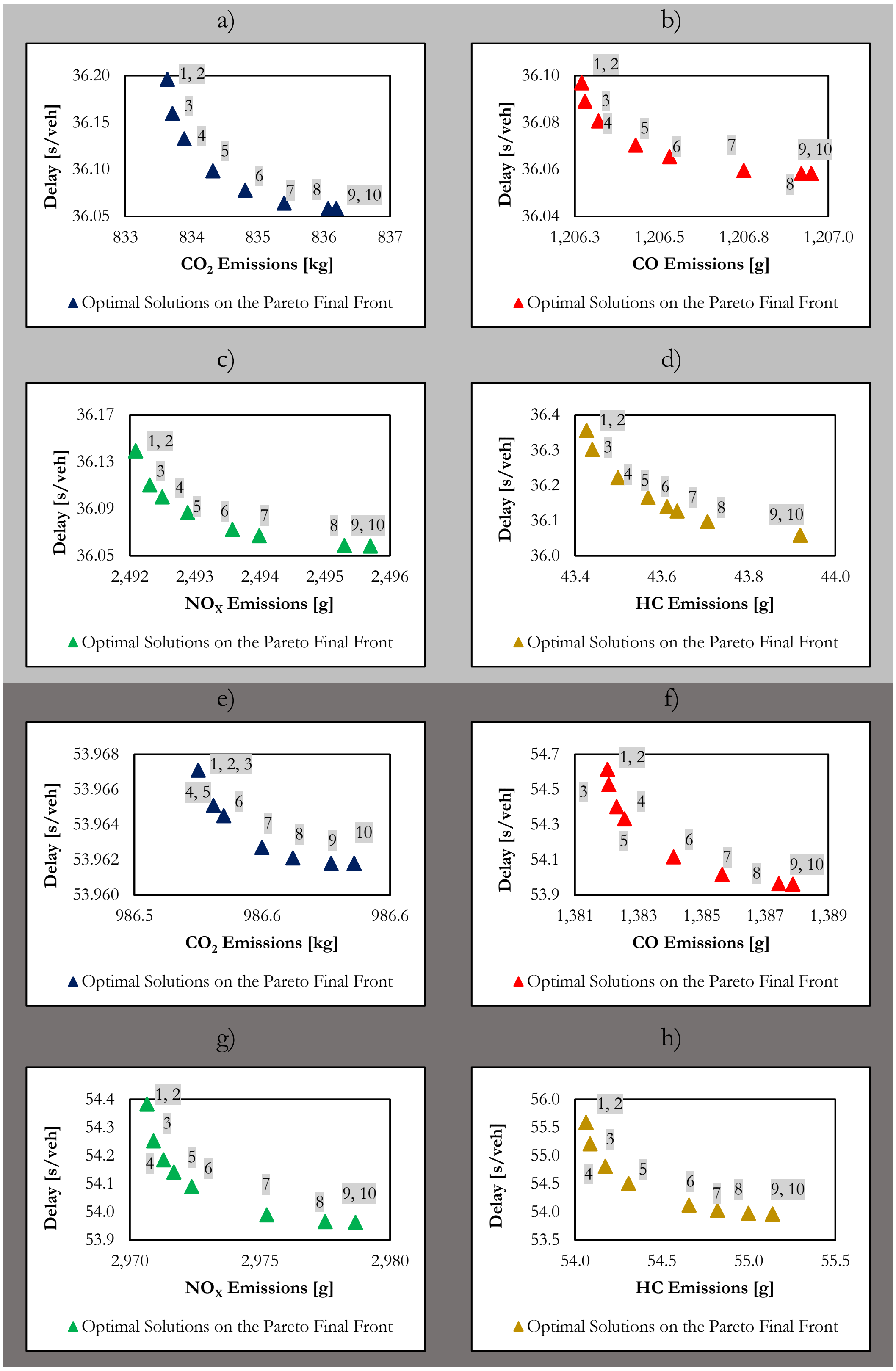


Figure 6.19 The approximate Pareto front for scenario 1 under different traffic conditions: 100% demand factor (a, b, c and d) and 125% demand factor (e, f, g and h).

Table 6.16 Solution lists of the spacing values for the scenario 1 considering objective function criteria

Demand Level	Solution	Delay vs CO_2			Delay vs CO			Delay vs NO_X			Delay vs HC		
		Spacing [m]	Delay [s/veh]	CO_2 [kg]	Spacing [m]	Delay [s/veh]	CO [g]	Spacing [m]	Delay [s/veh]	NO_X [g]	Spacing [m]	Delay [s/veh]	HC [g]
100%	1	196	36.2	833.6	207	36.1	1,206.3	202	36.1	2,492.1	181	36.4	43.4
	2	196	36.2	833.6	207	36.1	1,206.3	202	36.1	2,492.1	181	36.4	43.4
	3	200	36.2	833.7	209	36.1	1,206.3	205	36.1	2,492.3	184	36.3	43.4
	4	203	36.1	833.9	210	36.1	1,206.3	207	36.1	2,492.5	193	36.2	43.5
	5	207	36.1	834.3	212	36.1	1,206.4	209	36.1	2,492.9	199	36.2	43.6
	6	211	36.1	834.8	213	36.1	1,206.5	212	36.1	2,493.6	202	36.1	43.6
	7	214	36.1	835.4	216	36.1	1,206.8	213	36.1	2,494.0	203	36.1	43.6
	8	217	36.1	836.1	217	36.1	1,206.9	217	36.1	2,495.3	207	36.1	43.7
	9	218	36.1	836.2	218	36.1	1,207.0	218	36.1	2,495.7	218	36.1	43.9
	10	218	36.1	836.2	218	36.1	1,207.0	218	36.1	2,495.7	218	36.1	43.9
125%	1	199	53.96	986.6	181	54.6	1,382.0	183	54.4	2,970.7	184	55.6	54.1
	2	199	53.96	986.6	181	54.6	1,382.0	183	54.4	2,970.7	184	55.6	54.1
	3	199	53.96	986.6	184	54.5	1,382.1	187	54.3	2,970.9	188	55.2	54.1
	4	200	53.96	986.6	189	54.4	1,382.3	189	54.2	2,971.3	191	54.8	54.2
	5	200	53.96	986.6	190	54.3	1,382.6	191	54.1	2,971.7	198	54.5	54.3
	6	201	53.96	986.6	193	54.1	1,384.1	193	54.1	2,972.4	205	54.1	54.7
	7	201	53.97	986.6	196	54.0	1,385.7	200	54.0	2,975.3	210	54.0	54.8
	8	202	53.97	986.6	202	54.0	1,387.4	204	54.0	2,977.5	212	54.0	55.0
	9	203	53.97	986.6	204	54.0	1,387.9	206	54.0	2,978.7	215	54.0	55.1
	10	203	53.97	986.6	204	54.0	1,387.9	206	54.0	2,978.7	215	54.0	55.1

6.3.5. Policy Implications

The findings confirm that spacing of roundabouts ranging from 180 to 222 m achieves moderate improvements in both delay and emissions of the corridor when compared to a low distance value. This means that the current spacing (~167 m) does not completely optimize traffic operations along the corridor. The location of the intersection in further distances (high spacing) is a constraint for the downstream intersections. This is especially true under high traffic demand levels.

The optimal spacing values obtained in this paper were much lower than those suggested by several guidelines (68, 71, 72), which were based on American study-cases. Conversely, some of the optimal spacing values were close to those recommended by European guidelines (69). The findings also confirmed that the spacing has a great impact on vehicle delay and emissions along the corridor, as mentioned by a previous research (41).

Hence, an assessment of a hot spot traffic segment of a given corridor must be carefully done. This includes a proper traffic control implementation together with an optimization of spacing design according to the location-specific operational or emission needs. Moreover, in terms of policy implications, such design criteria should not be centered only to improve traffic performance or to reduce global pollutants as CO_2. It must be taken into account which major environmental concerns in a certain region are presented (for instance to reduce NO_X and HC pollution levels).

It is well-known that the rapid growth of cities has strained the capacity to provide satisfactory levels of service such as transportation, education, or sanitation (91). Transportation planning is currently being challenged with a broader planning (92). The lack of consistent and well-experimented planning policies has contributed to the urban sprawl phenomenon in many countries. Therefore, a mixed land-use policy with a suitable transportation design strategy is essential to fight against sprawl as well as to maintain or improve overall network performance. Focusing on the transportation sector, several other strategies may be developed, such as policies and incentives for encouraging the use of public transportation systems (93) or implementation of traffic restriction measures on urban areas (94).

It should be mentioned that the simple analysis segment of the corridor does not solve all issues associated with inefficient urban planning per se. Nonetheless, if overall network performance is improved, the utility of spacing as a policy management measure on urban areas can be considered.

6.3.6. Conclusions

This research analyzed a specific segment of an urban corridor with closely-spaced intersections (single-lane roundabout and traffic light spaced approximately 167 m), which presented weak traffic performance and environmental levels. To mitigate these issues, the traffic light was replaced by a single-lane roundabout, and the results were compared with the existing situation under different demand levels (actual traffic and an expected traffic growth of 25%).

The paper also performed an optimization analysis for the best traffic control by varying the spacing between those intersections with the main purpose of improving delay and CO_2, CO, NO_X and HC vehicular emissions. The analysis was based on a microsimulation approach, using a traffic model integrated with an emission methodology. As a solution algorithm, NSGA-II was used to search the optimal solutions for the proposed problem.

The methodology of this paper can be outlined in the following steps:

1) To identify a highly-congested specific segment of a given corridor that has a great impact on the traffic operations;

2) To understand the causes that led to the inefficient operational and emissions levels of such segment;

3) To implement and compare different traffic control treatments to improve traffic performance and emissions outcomes;

4) To select its suitable and feasible (taking into account corridor-specific needs) location in relation to downstream and upstream intersections, for the best traffic control;

5) To define whether there is a need to fulfill the emissions' levels for a specific pollutant during the optimization of the spacing between intersections.

The following findings were obtained for the actual traffic demand:

- Single-lane roundabout led to the lowest number of vehicle stops, 24% less average delay and 57% less queue length; Also, it was environmentally better than the traffic light solution (5-7%, depending on the pollutant);
- For the above traffic control, an additional decrease of emissions of 6% may be expected by adopting an optimized spacing of about 207 m from an upstream roundabout when compared to the existing spacing.

The following findings were found in future expected demand level:

- Single-lane roundabout yielded lower emissions than traffic light (16-27%, depending on the pollutant), and delay and queue length were shortened by 44% and 64%, respectively;
- The optimal spacing for CO_2 range from 199 to 204 m, while spacing values for local pollutants of approximately 180 m can be adopted. Considering a spacing value of 200 m, vehicular emissions and average delay were predicted to be reduced in more than 5 and 6%, respectively when compared to the existing spacing.

Overall, the variation of delay and different pollutant emissions pointed out to the moderate impact of spacing on delay and emissions along corridors using the proper traffic control strategy.

6.3.7. Acknowledgments

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6.4. References

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7. CONCLUSIONS AND FUTURE RESEARCH

This chapter highlights the contribution of the research, summarizes the general and specific research findings. Specific considerations regarding the implementations and some unresolved issues that deserve future research attention are also identified.

7.1. Contributions of the Research

The main motivation of this PhD research was to evaluate the impact of corridors with conventional and innovative roundabouts, traffic lights and stop-controlled intersections on traffic performance, global and local pollutant emissions and pedestrian safety.

The parameters related to vehicle activity data (instantaneous speed and acceleration-deceleration) and driving behavior patterns were fully characterized. The analysis also addressed several corridor's geometric and operational characteristics (spacing between intersections, entry deflection angle, number of legs, intersection control, crosswalk treatment, traffic and pedestrian flows, split distributions and speeds).

The development of a methodology to assess these variables was also a contribution of this work. The methodology was intended to assure reliability of traffic operations from well-established scenarios that were described in terms of traffic performance, emissions and pedestrian safety in real-world corridors.

While studies on the assessment of roundabouts at isolated intersections are extensive, there was a lack of knowledge about the impact of operational and geometric characteristics of corridors with roundabouts on traffic, especially for environmental and safety purposes. This PhD thesis offers a line of research that produced methods for transportation planners and decision-makers to select suitable and feasible traffic control strategies along arterials considering location-specific concerns.

Examples of these applications were described and presented in this doctoral thesis and in publications in scientific journals and conferences that resulted from this work and include: *a*) advantages and drawbacks of implementing corridors with different control treatments on traffic performance, emissions and safety (especially for vulnerable users as pedestrians); and *b*) integration of a microsimulation platform into a corridor-based system analysis.

The introduction and research objectives were presented in detail in **Chapter 1**. **Chapter 2** addressed the environmental and operational benefits and limitations of new roundabout layouts, as is the case of turbo-roundabouts in isolation along an urban corridor. Subsequently, this thesis explored the impacts of conventional roundabout corridors by examining the hotspot emission locations in different corridor segments and by analyzing corridor design features impacts on pollutant emissions (**Chapter 3**). Then, a comparison of corridors with traditional forms of intersections (conventional single-lane roundabouts, signalized and stop-controlled intersections) (**Chapter 4**), and new intersection layouts (turbo-roundabouts) (**Chapter 5**) was conducted. Once corridor roundabouts specificities evaluated, a multi-objective analysis was done to improve their efficiency in **Chapter 6**.

The main contributions of this research can be summarized as follows:

1. Assessment and quantification of roundabout corridors impacts on traffic performance, emissions and safety variables;
2. Microscopic simulation of traffic, emissions and safety linked with a multi-objective analysis tool capable of analyzing and comparing corridors with different traffic controls;
3. Identification of trade-off among outputs, namely: traffic performance parameters (delay and number of stops), emissions (CO_2, CO, NO_X and HC), and pedestrian safety (relative difference between pedestrian and vehicle speed);
4. Correlation of geometric variables of corridors, pedestrians' crosswalk location and traffic flow characteristics with the above-mentioned outputs.

The findings of this research can be tailored to assess real-world corridors analysis, and lay the ground for a reliable and accurate methodology to compare several mobility indicators across alternative traffic controls.

7.2. Summary of Research Findings

7.2.1. General Findings

In summary, the general conclusions of this PhD research can be outlined as follows:

1. The principal design features that impact acceleration-deceleration patterns and the spatial distribution of CO_2, CO, NO_X and HC emissions differ considerably between roundabout corridors (spacing between adjacent intersections) and isolated roundabouts (entry deflection angle);
2. The research shows that spacing influences optimal crosswalk locations along roundabout corridors, especially in the case of short distances between adjacent intersections (< 200 m). This happens because vehicles are not able to attain and maintain cruise speeds along mid-block and therefore reduced the potential risk of pedestrians;
3. Turbo-roundabout in series along urban corridors slightly increased emissions compared to conventional two-lane roundabout corridors (1-5%, depending on the pollutant). Also, emissions could be decreased on a corridor with closely-spaced turbo-roundabouts by changing the location of a specific intersection to increase the spacing (within feasible distances and land use constraints);
4. In very specific situations (i.e. high through traffic demand and unbalanced traffic flows between main roads and minor roads), corridors with roundabouts perform worse than equivalent corridor with stop-controlled intersections (12% more emissions). Further, a corridor with coordinated traffic lights at the arterial level generated higher emissions (> 6%) compared with roundabouts. The research results also confirmed the advantages of implementing roundabouts when the main concern was the number of vehicle stops.

7.2.2. Specific Findings

Turbo-Roundabouts in isolation – Chapter 2

- It was found that, under high traffic demands (entry and conflict traffic flows higher than 1,000 vph), vehicles circulating in isolated turbo-roundabouts generated more emissions than did at the multi-lane roundabouts (19%, 23%, 19% and 29% for CO_2, CO, NO_X and HC, respectively);
- Under low and moderate values of conflicting traffic (from 100 to 400 vph), there appears to be an increase in emissions at turbo-roundabouts comparing with multi-lane layout (13%, 16%, 12% and 20% for CO_2, CO, NO_X and HC, respectively).

Identification of emission hotspot along roundabout corridors – Chapter 3

- Downstream sub-segments along corridors with equally spaced roundabouts were identified as the emissions hotspots (overall contribution on emissions exceeded 34% of the entire corridor) both in absolute terms and per kilometer travelled. However, when considering corridors with unequally spaced roundabouts, the hot spot emission location per unit distance, which was 9% higher than the average corridors values, occurred at the circulating areas sub-segments;
- The analysis of CO_2 and CO emissions for different values of spacing and entry deflection angle demonstrated that the spacing had a moderate impact on the spatial distribution of emissions along corridors, while the entry deflection affected marginally emissions at those traffic facilities;

Assessment of corridors with different forms of intersections controls – Chapter 4

- At the corridor level, four single-lane roundabouts (two four-leg and two three-leg) had lower stop-and-go situations (-50%), and performed environmentally better than a solution of equivalent corridor with traffic lights (4% to 5%, depending on the pollutant). However, a two-way stop-controlled traffic operation system was the best design solution: 12% less vehicular emissions and approximately 16% lower travel time;
- At the intersection level, four-leg roundabouts yielded the lowest number of vehicles stops and fewer emissions than traffic lights (8% to 19%, depending on the pollutant) at four-leg intersections. Conversely, three-leg roundabouts generated more emissions than traffic lights (2% to 14%, depending on the pollutant). Two-way stop-controlled decreased average emissions compared with single-lane roundabout layout (3% to 24%, depending on the intersection), and shortened travel time by 6% to 23% (depending on the intersection).

Turbo-roundabouts in corridors – Chapter 5

- Downstream (acceleration) segments were identified as the emission hotspots along turbo-roundabout corridors both in absolute terms (overall contribution on emissions was higher than 30%) and per kilometer traveled. The impact of spacing between turbo-roundabouts was found to be significant in the spatial distribution of these emissions;

- Compared to traditional multi-lane roundabout corridors, vehicles through turbo-roundabout corridors had on average higher travel time and generated more emissions. However, the difference in average emissions between layouts was not statistically significant at 95% confidence level;
- Under high-congestion levels (near saturation), adjacent turbo-roundabouts spaced lower than 180 m yielded an additional increase in overall corridor emissions by 8%, 4%, 5% and 11% (for CO_2, CO, NO_X and HC, respectively) compared to a spacing of 240 m.

Multi-objective analysis on corridors – Chapter 6

- Albeit safe for pedestrians, crosswalks near the circulating carriageway of roundabouts (< 10 m) resulted in high vehicle delay and CO_2 emissions levels. Distances of 15, 20 and 30 m were found to be suitable, regardless of pedestrian and traffic flow levels. Under high traffic demand levels, crosswalk location near the mid-block (55 to 60 m) sub-segment between two closely-spaced roundabouts improved capacity and emissions values without negatively affecting pedestrian safety;
- Considering local pollutant criteria (CO, NO_X and HC), optimal crosswalk location was found to be 10 to 15 m from the circulatory road, and near the mid-block between adjacent closely-spaced roundabouts, regardless of the site-specific operational and geometric conditions;
- The analysis of the relative crosswalk location for different values of spacing, demonstrated the impact of spacing ($R^2 > 0.72$) on optimal crosswalk locations along the mid-block section: if the spacing is lower than 100 m then crosswalk can be located at about 20-30% of the spacing length; if spacing is in the 140 to 200 m range then crosswalk can be placed at the midway position (50% of the spacing);
- The analysis of a specific segment of an urban corridor with closely-spaced highly-congested intersections (single lane and traffic light) resulted in notable improvements (57 and 6% less average delay and emissions, respectively) when a fixed-cycle traffic light was replaced by a single-lane roundabout. Using the best traffic control, the optimization of the spacing dictated improvements in corridor operations. For a spacing value of 200 m, a decrease of vehicle delay and vehicular emissions in more than 6% and 5%, respectively, can be predicted when compared to the existing spacing of 167 m.

7.3. Implementation Considerations

The main contribution of this PhD thesis is the integrated analysis of three distinct fields: traffic performance, environment and safety modeling along corridors with different forms of intersections. Also, it includes an optimization method that improved the corridor's efficiency according to the location-specific needs.

The findings were very encouraging, demonstrating the main operational and geometric features and issues of roundabout corridors. In addition, the microsimulation platform was proved to be useful to describe the interaction between corridor's design features and outputs that in many cases contradicted to each other.

The proposed methodology is suitable to assess traffic, environmental and pedestrians' safety that emerge from new traffic facilities and/or traffic solutions prior their construction as well as in the redesign of existing corridors that are not operating well (e.g. corridor with low CO_2 emissions but high CO or NO_X levels).

In summary, this research contributes for decision making by traffic management entities in the following areas, such as:

- Quantification of the traffic performance, environmental and safety consequences of the installation of specific traffic control treatments along a corridor;
- Selection of optimal location of traffic interruptions by changing the distance between intersections;
- Guidelines for the selection of pedestrian facilities (locating the crosswalk to assure the safety for pedestrians) at the corridor level;
- Analysis and comparison of traditional and innovative roundabout layouts along corridors according with traffic flow, directional split distribution and geometry of the corridor and intersection;
- Optimal definition of the geometric parameters of roundabout and turbo-roundabout corridors to achieve balance in predefined objectives regarding traffic calming and concomitantly minimize global and local pollutant emissions impacts.

It must be noted that the optimization and feasibility of this methodology can be a complex task. For instance, the replacement of a specific traffic control within a corridor or the changing of a crosswalk or intersection location could represent an improvement of corridor-specific operations, but this may not be agreeing with drivers or pedestrians comfort levels. Moreover, there is a subjectivity regarding the relevance given to a certain criterion. The optimization used in this work assumed an equal weight for safety, emissions and traffic performance variables which may not correspond for the local authorities, road users or non-motorized modes expectations. Such aspects must be considered during the different phases of the analysis.

7.4. Limitations and Recommendations for Future Work

Several limitations must be outlined.

The effect of distinct driver behaviors and time-demand along corridors on tailpipe emissions, traffic performance and pedestrian safety were not considered. In fact, the data collection procedure was carried out by respecting site-specific speed limits and similar driving patterns, as well as under very limited demand periods (peak hours only).

This research did not address the safety impacts of roundabouts and turbo-roundabouts (both in isolation and along corridors) for cyclists and motorcycles. It should be highlighted the fact that one of the disadvantages documented in the introduction section was potential safety issues at roundabouts for these transport modes.

All emission results presented in this research were based on emission factors that represent a limited car fleet (gasoline, diesel or hybrid electric). However, the focus of this thesis was the introduction of a practical method to assess corridors rather than a development of an extensive database. Thus, the use of all vehicle types was not necessary. Note that the onboard characterization of emissions of all representative vehicles of Portuguese, Spanish or Dutch fleets would be practically infeasible.

As mentioned before, the methodology assumed an equal weight for the different criteria (safety, CO_2, CO, NO_X, HC, delay) without being in consideration the subjectivity associated for these cases.

Another limitation was that the traffic model used in this research ensure that vehicles not collide, and therefore simulated conflicts might be different from observed conflicts or crashes. Usually, safety assessment depends on crash data analysis that may not always be available or take a long time to generate.

Lastly, this thesis discarded the impacts of several roundabout geometric features on traffic operations and emissions, and whose design can result in trade-off among outputs. Some of these geometric elements are the inscribed circle diameter, the circulatory roadway width, approach width, the departure width, the entry and exit widths or entry and exit radius.

Despite these limitations the potential of the methodology developed in this can be applied using other emission rates (from different vehicle types and countries car fleets), specific driver behaviors, multi-objective algorithms and input geometric data. Thus, the main focus was on the relative impact of corridors on traffic performance, emissions and safety, and less concern was given to absolute values.

The following tasks can be explored in future work, namely:

- To assess different driving behavior styles with significant variations on speed limits, dangerous driver's behavior as vehicles approach and enter a roundabout. Cluster analysis can be applied in this case to identify some meaningful patterns among variables;
- To characterize the impacts of roundabout corridors during an entire day (covering off-peak periods) to generalize the applicability of the research findings;
- To explore the benefits and limitations of roundabout corridors from cyclists and pedestrians. For example, locating a crosswalk far from roundabout exit section can increased pedestrian travel time and travel distance which may lead pedestrians crossing outside crosswalk, and therefore reducing their safety.
- To quantify the traffic noise levels in the vicinity of corridors with roundabouts or other types of intersections such as signalized and stop-controlled intersections;
- To validate the safety results specifically for the traffic conflicts at roundabout corridors. This could be done by developing advanced mathematical models to predict conflicts

and crashes as a function of operational, geometric and driver behavior variables. This might also help to improve the accuracy of safety assessment using a microsimulation approach;

- To investigate the effect of heavy-duty vehicles that is critical from environmental and noise perspectives. It must be mentioned that almost corridors studied in this research include low rates of heavy-duty vehicles on their car fleet;
- To look at hybrid treatments (e.g. combination of signalized and roundabouts layouts) as way to improve traffic operations. Still, the singular effect of other forms of intersections such as actuated traffic lights, signalized roundabouts or turbo-roundabouts layouts along arterials would be also explored.