Interpreted modeling for safety and emissions at roundabouts in corridors

Projeto de Tese II

Aluno: Paulo Jorge Teixeira Fernandes – paulo.fernandes@ua.pt

Orientadores: Prof.ª Doutora Margarida Coelho, DEM-UA (margarida.coelho@ua.pt); Prof. Doutor Nagui Rouphail, North Carolina State University (rouphail@eos.ncsu.edu)

Docente: Prof. Doutor Vítor Costa – v.costa@ua.pt
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Summary

During the past few years, roundabouts have experienced a significant increase and are now widely used in many countries. Scientific research has shown that the operational performance of roundabouts installed at isolated intersections depends on its design features and also of the traffic streams characteristics, which lead to a trade-off among capacity, safety and emissions. Furthermore, there is a lack of evidence about the vehicle’s performance of roundabouts in a series along a corridor in terms of emissions and fuel use.

The goal of this Doctoral research will be focused on a comparison of energetic and environmental performance of different roundabouts in corridors. To achieve the proposed objectives, several roundabouts corridors will be analysed using empirical approaches, as well as traffic and emission models. Using multi-objective analysis, this work will expect to identify the most optimized traffic system both in terms of energy use, emissions and traffic performance.

This report is an ongoing work from the course “Thesis Project I” in which a review of the technical literature, the main motivations, the main objectives as well as the research tasks were developed.

In this course, Thesis Project II, a more comprehensive description of the methodology used on this thesis topic is performed. More specifically, it is focused on the description of the selected methods to accomplish the tasks of this thesis. Moreover, some preliminary results and future tasks are also provided.

Section 1 highlights the objectives and the structure of this research, followed by the update of the technical literature review (see Section 2). The presentation of the selected models is made in the section 3. This report finishes outlining the developed work in Section 4.
1. Introduction

1.1. General Statement of the Problem
Roundabouts are proven to be a safety countermeasure for intersections (1). Roundabouts reduce the unnecessary number of stops for vehicles and improve the capacity, compared to stop-controlled intersections. Roundabout design imposes different driver behaviours compared to signalized or stop-controlled intersections. Roundabout design causes drivers to decrease vehicle's speed and decelerate as they approach the roundabout, and enter the circulating traffic and accelerate as they exit the circulating traffic. Roundabout operation is affected by different levels of vehicle demand at entry approach and in circulating lanes. During congested periods long queues at the entrance or blockage in the circulating and exiting lanes may occur. In order to take advantage of operational benefits of roundabouts, there has been an increasing interest among engineers and designers to build multi-lane roundabouts for higher flow rates or higher speed corridors.

During the last three decades, roundabouts have gained increased popularity and are now widely used in many countries. Scientific research has shown that the operational performance of individual roundabouts depends of its geometry and also of the traffic streams characteristics, which leads to a trade-off between safety and emissions. Furthermore, there is a lack of evidence about the vehicles’ performance in roundabouts systems installed in corridors in terms of emissions.

1.2. Objectives
The main objective of this Doctoral research is to assess the impact of the presence of roundabouts systems at corridors on traffic performance, fuel use and emissions.

To accomplish the established objectives, a wide range of geometrics, traffic and crashes data will be obtained for multi-lane roundabouts located in corridors. The study will be focused on the effects of different traffic parameters (pedestrians influence, geometry configuration, distance between each roundabout within the corridor, and traffic volumes) on energy consumption and emissions.

Thus, the main objectives of this research:

1. To gain an understanding of the effect between different specific geometric features of corridors with roundabouts (e.g. distance between consecutive roundabouts, circulating areas, number of approach lanes, deflection angle, land use parameters) with the environmental variables, in particular, carbon dioxide (CO₂), carbon monoxide (CO), nitrogen oxides (NOₓ) and hydrocarbons (HC) emissions;
2. To compare corridors with roundabouts emissions from well-characterized scenarios according to the Portuguese reality;
3. To perform a multi-objective analysis to identify the most optimized traffic system both in terms of traffic performance, energy use and emissions.
1.3. Structure of the thesis

In this section the structure of the thesis is suggested. It is proposed a layout composed of seven chapters:

1. Introduction and Objectives
2. Review of technical literature
3. Safety impact on roundabouts corridors
   3.1. Methods
   3.2. Main Results
   3.3. Concluding remarks
4. Energy and emissions impact on roundabouts corridors
   4.1. Methods
   4.2. Main Results
   4.3. Concluding remarks
5. Multi-objective analysis
6. Conclusions and Future Work
7. References

The introduction will set the problem statement, state the objectives and will explain the contribution of the research.

The review of the technical literature will provide a critical assessment of previous research efforts and its relationship with the present work.

Chapters 3 and 4 will describe the developed methodology and results obtained, for each impact. First, Chapter 3 will describe the safety impact analysis (namely the crash data inventory as well as the development of crash prediction models for corridors with roundabouts) and its results. Chapter 4 will be dedicated to the description of numerical models to assess the emissions impact.

Chapter 5 will combine both domains (safety and emissions) and describe the development of an algorithm to perform a multi-objective evaluation with the main goal of optimizing roundabout corridors systems in the field of emissions and safety.

Chapter 6 will be a critical analysis of the work performed, a summary of the contributions and will point out future directions of research. Finally, Chapter 7 will be the list of references used.
2. Review of the Technical Literature

This chapter offers a review of the most relevant studies focused on the general analysis of roundabouts. The literature review is divided into four main sections. Section 2.1 describes a brief overview of roundabouts topic. Then, section 2.2 presents the most significant studies in corridors with roundabouts. In turn, section 2.3 focuses on the existing research on roundabouts installed at isolated intersections in terms of capacity, emissions and safety. Finally, the most important conclusions of the literature review and the major motivations of this thesis topic are explained in the section 2.4.

2.1. Introduction

One-way circular intersections were created by Eugene Henard, in 1877 (2). Since the adoption of a yield-at-entry regulation in 1966 in Great Britain (3), roundabout design has evolved from the use of larger circles with emphasis on merging and weaving to small compact roundabouts.

There has been a significant increase in the deployment of roundabouts in the past years in the North-America and in Europe. Currently there are approximately 2,300 and 130 roundabouts in place across the United States and Canada, respectively (4). Similarly, the number of roundabouts constructed in several countries such as Germany, Italy, Portugal, Spain and United Kingdom has been relevant. In France, for instance, it is estimated that there are more than 30,000 roundabouts (5), and in Sweden over than 2,000 roundabouts have been implemented since the mid 1980s (6).

From that point on, there has been high interest and significant research on roundabouts because of the simplicity in their design, operations and safety (1). These traffic facilities provide higher capacity levels in intersections compared to stop-controlled intersections (7) and are most robust concerning to the reduction of the unnecessary number of vehicle stops (8). The empirical delay formula for roundabouts in the Highway Capacity Manual (8) demonstrated that the delay at roundabouts can be either small or the same as verified in all-way-stop-controlled intersections. Regarding the safety, there is a greater consensus to the benefits of roundabouts for motor vehicles and for pedestrians compared to other intersection forms (1). According to the Federal Highway Administration (FHWA), there was a significant reduction in injury crashes of converting signalized and two-way-stop-controlled intersections to roundabouts (7).

2.2. Roundabouts in corridors

In this context, roundabouts in corridors represent a traffic calming technique with the main aim of improving road safety by reducing vehicles speed. Moreover, they enable U-turns on access restricted roadways (divided roadways with turn restrictions) and allow flexibility in maximizing intersection capacity without the need for excess turn lane storage or additional receiving lanes (9).
A typical concern for use of roundabouts in a series along a corridor is how flow will be impacted. Along a main corridor with traffic signals, an effort is usually made to coordinate the signals or provide for progression on so that a significant number of vehicles can proceed through the arterial without being stopped. A series of roundabouts forces all vehicles to slow at every roundabout (9). Another concern about corridors with roundabouts is that how vehicle emissions will vary according to the geometrical characteristics of roundabouts along the corridor. These specifics design features could have a significant effect on pollutant emissions, namely in urban and rural areas.

Several researchers have investigated and developed algorithms for signalized corridors to improve safety (10, 11) or to minimize fuel consumption and emissions (12, 13). The few studies carried out in corridors with roundabouts raise some uncertainties about their effectiveness. Hallmark et al. (14) recorded marginal benefits in improved traffic flow of roundabouts within signalized corridors over stop and signal control intersections. In (15), an on-road assessment of the emission impacts of roundabouts compared with stop intersection and roundabout with signal control intersection along two corridors was conducted. The findings suggested that, under uncongested conditions, roundabouts did not perform better than four-way, or signal controlled intersections in the same corridor. Nonetheless, each studied corridor (14, 15) only contained one roundabout throughout its length. Just recently, a lane-based micro-analytical network model was developed and implemented in aaSIDRA (aaTraffic Signalised and Unsignalised Intersection Design and Research Aid) Intersection Model (16). This model allows estimating the impacts of lane-utilization on network performance and can be applied in roundabouts systems, but is not able to assess emission impacts of those facilities. Krogscheepers and Watters (17) 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 for high demand scenarios.

2.3. Roundabouts at isolated intersections

Roundabouts are usually analyzed at three levels: capacity, emissions and safety. This section provides a brief summary of the most important studies with respect to the operational performance of roundabouts in these fields.

2.3.1. Capacity

The majority of the existing roundabouts capacity models are based in three methodologies: fully-empirical, gap acceptance and simulation (18). Any of methodologies cannot fully describe the complex behavioral and physical processes involved in roundabout approaches movements.

Empirical regression models were created through statistical multivariate regression analyses with the main aim of establishing relationships between
observed entry capacity, circulating traffic flows and other variables with a meaningful impact on capacity. However, they are subjected to statistical and sampling constraints, namely: a) reduced transferability among different case studies; b) only included oversaturated traffic flow conditions, and c) the large amount of data collection to perform its calibration (18). The LR942 Linear Regression Model (6), French Girabase Model (19) or based on Neural Networks are the well-known empirical regression models (20).

Gap acceptance modes focused on the distribution of gaps and also on the usefulness of these gaps to the approaching vehicles, but are limited by the relatively weak relationships between these models and design features (18). The estimation of the critical gap (minimum time gap in the circulating stream which an entering driver will accept) and the follow-on headway (time between two consecutive queued vehicles) parameters is fundamental during the process. The best-known gap acceptance model for roundabouts was created by Troutbeck, in 1989 (21). The circulating headway distribution was the Cowan M3 distribution, in which a proportion of vehicles was assumed to be aggregated with a fixed headway while remaining vehicles had exponentially distributed headways. Wu (22) introduced a universal procedure for calculating the capacity at non signalized intersections by using a queuing theory. The High Capacity Manual (HCM) included a gap acceptance model (8) based on the number of entry and circulating lanes, and whether the entry lane was nearside or offside.

In summary, the main differences of above approaches lies in the assumed headway distributions, and the formulation of the relevant parameters such as the proportion of clustering (18). Nonetheless, it is recognized that they still require more improvements. First, the limited priority process in roundabouts is rarely included (23). Second, it is demonstrated that pedestrian’s crossings have effects in the capacity of entry and exit sections of the roundabouts (24). Third, there is a lack of reliable estimations about some of parameters that are present in most gap-acceptance formulas (25). Fourth, existing capacity models are not able to assess the overall performance of unconventional roundabouts and innovative solutions, such as the turbo-roundabouts.

The stochastic microscopic simulation is an alternative approach that provides a good flexibility in terms of the assessment of capacity models in roundabouts. Their validation and reliability is highly dependent of an accurate representation of vehicle–vehicle interactions, which can be difficult to replicate, even with actual observed data (18).

In (26), the traffic delay of roundabouts was compared to yield control, signal control, two-way stop control, and four-way control intersections by using aaSIDRA model without any field data. The scenarios for roundabouts included different direction left turns (10%, 20% and 30%) under different traffic flows while two-way stop control, four-way stop control, signal control, and yield control were modeled with a 10% left turn. Roundabout showed as the most effective for heavy traffic intersections with two-lane approaches. Alternatively, Meredith and Rakha demonstrated that, under over-saturated conditions in the approach lane (e.g. traffic flows below 500vph), signal control was not necessarily worse than
roundabout (27). Bastos Silva and Vasconcelos (24) studied the effect of exit pedestrian crossing in the upstream entry capacity and average speed, under different levels of motorized and pedestrian demand. The findings suggested that the crosswalk near to the exit provided a decrease in terms of traffic performance. For high traffic flows, the authors also recommend the possibility to install the crosswalks further away from the exit. In the research of Zheng and Qin (28), it was demonstrated that roundabouts recorded lower traffic delays than pre-timed traffic signals at intersections with moderate queue lengths. They also predicted that roundabouts efficiency decreased as queues length increased.

2.3.2. Emissions

In spite of having an extensive body of research in macroscopic (e.g. COPERT (29), MOBILE6 (30) or TREM (31)), mesoscopic (e.g. TEDS (32)), and microscopic (VT-MICRO (33), CNEM (33), VSP (34) and MOVES (35)) emission models, their applications on roundabouts case studies are very limited.

COPERT (29) and MOBILE6 (30) models, for instance, are not recommended in micro scale impact of corridors with traffic interruptions (e.g. pay tools, roundabouts) (36, 37) since they assumed that emission rates are constant for all speed ranges. The mesoscopic aaSIDRA intersection model includes an emission module that uses a four-mode elemental model (cruise, deceleration, idle and acceleration to cruise) to estimate fuel consumptions and pollutant emissions. Nevertheless, the impact of each stop and go cycles are not taken into account (16). Traffic and Emission Decision Support (TEDS) model can be applied in urban corridors, but only single lane roundabouts are included in this analysis (32).

The microscopic models aim to provide accurate emissions estimates at the roundabouts operation levels. One of the most representative and widely accepted micro-scale models is the Comprehensive Modal Emission Model (CNEM) (33). This model provides accurate emissions estimation of Light-Duty Vehicles (LDV) under different vehicle’s operating modes. However, it lacks accurate emissions predictions at specific situations. VT-Micro is able to estimate emission rates and fuel consumptions per vehicles based on their instantaneous speeds and accelerations. VT-micro’s main disadvantage is the not direct inclusion of road grade parameter on emissions calculations (33). The Motor Vehicle Emission Simulator (MOVES) (35) allows estimating emission rates that vary with speed for particulate matter (PM) and greenhouse gases (GHG), but is most designed for the US reality.

Frey et al. (30, 34) developed the “Vehicle Specific Power” (VSP) methodology to estimate emissions for a single vehicle. On-board vehicle activity and emissions measurement using portable emissions measurement systems (PEMS) enable data collection under real-world conditions at any location traveled by vehicles on a second-by-second basis. This microscopic model is based on vehicle speed, acceleration/deceleration and road grade and has proven to be very effective in estimating instantaneous emissions for both light-
duty gasoline and diesel vehicles (38, 39) as well as in transit buses (40). A drawback of this approach is the little detail on fleet categories. Some previous studies have documented the effective use of VSP in analyzing emission impacts of roundabouts footprints in urban corridors both in the United States (e.g. (41, 42)) and in Europe (e.g. (41, 43-45)).

In the following paragraphs, the most relevant studies on roundabouts operations on vehicular emissions are reported. These studies are divided in two main groups: in the first group (41-44, 46, 47), only field data was used; in the second group (45, 47-50), a microscopic traffic model was linked with an external emission model.

The research of Coelho et al. (41) and Salamati et al. (44) should be highlighted. Coelho et al. (41) identified three characteristic speed profiles for a vehicle approaching both a single and multi-lane roundabouts: 1) no stop; 2) stop once and 3) multiple stops. They also found that the relative occurrence of these profiles were dependent of the entry traffic and conflict traffic flows. Based on these findings, the same authors developed regression models for approaching vehicles in single-lane roundabouts in urban areas. Built on above research, Salamati et al. (44) developed similar regression models in each approaching lane (right vs. left) at multi-lane roundabouts. Whilst methodologies of above studies are generalized to estimate emissions of roundabout footprints, its application cannot be extended to corridors. This is due that only traffic data related to the downstream and the circulating Areas of the roundabouts is considered. Even if proposed methodologies were applied for each roundabout along a corridor, the contribution of mid-block sub-segments, that is, within two consecutive roundabouts, would not be included.

In a Swedish study (46), an environmental assessment was conducted in order to compare signalized and yielded traditional intersections on arterials which were rebuilt as small single-lane roundabouts. The authors found that roundabouts can reduce emissions up to 29% and 21% of CO and NOx, respectively. Rakha et al. (51) demonstrated that both single and two-lane roundabouts yielded reduce traffic delays and CO emissions than one-way stop controlled in a three-way intersection. Anya et al. (43) showed that the environmental benefits posed by the 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. They also found that, at the corridor-level, turning movements from the main street produced higher total emissions while turning movements from the minor street produced lower total emissions after the roundabout implementation. More recently, Mudgal et al. (42) demonstrated that acceleration events at the circulating and exiting areas of roundabout contributed to more than 25% of emissions for a given speed profile.

The majority of the studies that used a micro-simulation approach focused on the comparison between single e multi-lane roundabouts with others intersections forms.
Mandavilli et al. (48) showed that both CO\textsubscript{2} and CO were reduced by 42\% and 59\%, respectively, on stop-controlled intersections which were replaced by roundabouts. Ahn et al. (49) used VISSIM and INTEGRATION in conjunction with air quality models (CMEM and VT-Micro) to compare emissions at a signalized, stop-controlled intersection and high-speed roundabout. The research showed that roundabouts yielded fewer delays and queue lengths, but produced more emissions than other alternatives. Chamberlin et al. (50) examined CO and NO\textsubscript{x} emissions produced by a three-leg intersection and a single-lane roundabout. The authors applied PARAMICS traffic model with MOVES and CNEM emission models. Both models estimated higher emissions for the roundabout when compared to the three-leg intersection. Likewise, Rakha and Jackson (47) employed INTEGRATION and VT-Micro to assess the environmental impacts of an isolated intersection served by a single-lane roundabout, traffic signal, all-way and two-way stop-controlled intersections. The roundabout predicted to have lower emissions of CO\textsubscript{2}, CO, NO\textsubscript{x} and HC, compared to other alternatives. Vasconcelos et al. (45) compared capacity, safety and emissions levels from a turbo-roundabout compared with a conventional single-lane and two-lane roundabouts. AIMSUN traffic model and VSP emission model were used. Assuming equal traffic demands, turbo-roundabout produced more CO\textsubscript{2} and NO\textsubscript{x} emissions than two-lane roundabout. Turbo-roundabout also showed as less robust concerning the directional splits of the entry traffic, namely when most of the vehicles turned left.

In summary, the candidate did not find a definitive conclusion about the environmental benefits from roundabouts operations. It should be noteworthy that the majority of them did not assess the capability of the traffic models to capture real-world vehicle power distributions. Previous studies demonstrated that microscopic traffic models tend to overestimate acceleration and deceleration values in relation to the observed data (52, 53).

2.3.3. Safety

Although the mostly of crashes at roundabouts results in property damage only (54), there are an extensive body of research focus on demand and improvement of crash models (7, 55-57) applied to roundabouts and intersections.

Nonetheless, the limited ability of above safety models to properly reflect crash causality has its source in cross-sectional analysis applied to the estimation of the intrinsically complex safety factors with highly aggregated and frequently poor quality of data. In this context, a clear theoretical approach to understand the theoretical assumptions that are behind of that models is needed. Moreover, the analysis of the different surrogate indicators associated to such models (58-60) and their potential for crashes estimation must be considered (61).

Dijkstra et al. (61) applied PARAMICS traffic model to predict the number of crashes, studying the possibility of the relationship between calculated traffic conflicts and crashes. Their findings suggested a Poisson log-linear statistical relationship between the number of simulated conflicts and observed crashes. Zheng et al. (28) performed an exhaustive analysis of roundabout crash patterns.
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in the United States (US) and developed a method to calculate crash type percentages. In (62), four crash prediction models were developed to evaluate the potential of speed as a measure of the road safety.

The micro simulation models have been played an important role in the field of safety analysis of roundabouts as occurred in emissions and capacity fields. FHWA developed a trajectory-based post-processing tool in its Surrogate Safety Assessment Model (SSAM) (63) to analyze and evaluate conflict points from some traffic models (e.g. VISSIM, AIMSUN). This tool processes trajectory files that store the speed, acceleration and position of each simulated vehicle during each simulation time-step and calculates surrogate safety measures and also classifies traffic conflicts based on conflict angle. Al-Ghandour et al. (64) developed conflict prediction models for five zones of single lane roundabout by using a Poisson regression, and compared them with simulated traffic conflicts obtained from SSAM model. The authors found good correlations between SSAM predicted conflicts and crashes, but recognized the need for additional research focus on the comparison between SSAM outputs and real crash data.

Huang et al. (60) proposed a two-stage procedure to calibrate and validate VISSIM to be used in conjunction with SSAM model to assess safety at signalized intersections. The authors concluded that the Mean Absolute Percent Error (MAPE) for total conflicts are predicted to be reduced from 43% to 24%. Data analysis results showed that there was a reasonable consistency between the simulated and the observed rear-end and crossing conflicts. However, they recognized that the simulated conflicts generated by VISSIM and SSAM were not good indicators for traffic conflicts which were generated by unexpected driving maneuvers such as illegal lane-changes in the real world. Vasconcelos et al. (65) recognized that despite some limitations regarding the nature of traffic models, SSAM is capable of evaluating the safety of different roundabouts layouts. Some authors suggested specific procedures to calibrate and validate simulation models for safety assessment but this is still an ongoing research field (66, 67).

2.4. Summary of literature review and motivations

From above-mentioned studies, two main relevant gaps in the research were observed:

- The assessment of the environmental and safety impacts were found in isolated roundabouts rather than a sequence along a corridor;
- It is noted that vehicle aspects of safety and fuel efficiency / emissions are treated independently and not in an integrated manner.

With these concerns in mind, one of the main motivations of this research is to investigate the impact of the different sub-segments of each pair of roundabouts that are installed in corridors on speed enforcement and pollutant emissions. The second motivation is to develop an advanced statistical model to predict crashes as a function of parameters such as traffic volumes, geometry and driver behavior conditions appropriate for Portuguese facilities.
This research seeks to contribute to a methodology that can incorporate the corridor geometric features and traffic stream characteristics to assess traffic performance, energy use and emissions. This methodology can be useful to the local authorities to the support of decisions in the field of capacity and emissions. The originality and scientific quality of the proposed research lie in the integration between these various fields of inquiry in order to understand their relationship and in the application of the developed methodology to any corridor with roundabouts. The integration of three areas on those uninterrupted flow facilities is worthy of research and analysis at this stage.
3. Methodology and Methods

The research work plan consisted of six interrelated tasks:

- **Task 1: Literature Review.**

- **Task 2: Development of numerical models to assess the emissions impact of vehicles in roundabouts installed at corridors.**
  
The numerical models include different sub-models to estimate vehicular emissions in urban corridors taking into account traffic characteristics and design geometric features.

- **Task 3: Development of a microscopic simulation platform of traffic, emissions and safety.**
  
  This approach attempts to represent traffic, emissions and road safety in order to evaluate traffic performance evaluation in world study cases.

- **Task 4: Application of the microscopic platform to examine alternative scenarios.**
  
  Both traffic systems will be compared, in order to study several alternative scenarios, namely, different traffic flow demands (peak and off-peak periods), change in pedestrian flows, and change in driver’s behavior (reduction of vehicle’s speed). This task also intends to compare overall corridor performance with individual roundabout and intersection.

- **Task 5: Application of a multi-objective analysis.**
  
  This task focused on the development of an algorithm to perform a multi-objective evaluation with the main goal of optimizing roundabouts corridors systems in the field of emissions and safety.

- **Task 6: Thesis Writing.**

A summary of the proposed tasks is depicted in **Figure 1**. The expected duration of this research is four years (1st of June 2013 – 31st of May 2017). The major tasks in the first year and second years will be to collect the data different roundabouts corridors as well as to investigate the main gaps of the current literature with respect of this thesis topic (task1). Additionally, the development of numerical emission models for corridors with roundabouts will be made (task2). In the second and third years (1st of September 2015 – 31st of August 2016), the modelling simulation platform, the integration of the emission module with the traffic model, as well as the calibration and validation procedures will be developed (task3). After that, traffic scenarios will be implemented and analysed (task4). The modelling platform will be supported by VISSIM model for traffic simulation, and Vehicle Specific Power methodology for emissions estimation. Next, a multi-objective analysis (task5) will be made in order to compare the results obtained for different systems of roundabouts. In the last year, the written of this thesis will be done (task6). The evolution of activities is described in **Table 1**.
Table 1: Evolution of the proposed activities.

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3.1. **Proposed Tasks**

In the following sections, the above tasks are presented and characterized. Since the literature review (task 1) was done during the course “Project Thesis I”, only the tasks 2, 3, 4 and 5 are explained.
3.1.1. Numerical model for emissions assessment in corridors

This section quantifies emissions impacts of corridors with roundabouts which includes a characterization of the different sub-segments along the corridor as well as the data needed to develop the numerical model.

3.1.1.1. Definition of sub-segments

Each roundabout corridor is divided into multiple sub-segments in order to quantify the emissions impacts and identify the segments with consistently high emissions. This level of segmentation is motivated by changes in speed as drivers decelerate while approaching the roundabout, transverse through the circulating lanes and accelerate while exiting the roundabout.

In order to be consistent with Highway Capacity Manual (HCM) Urban Street (Chapter 17) the corresponding Urban Street segment is defined from downstream yield lane from one roundabout to upstream of yield lane of the adjacent roundabout (in the direction of traveling) (68).

The proposed segmentation is illustrated in Figure 2 for a specific through movement. The exhibit shows two pairs of roundabouts RBT1/RBT2 and RBT2/RTB3, separated by (Urban Segments) B and C, respectively. Based on vehicle activity data and patterns in speed profiles, the four different sub-segments are identified. For each of these sub-segments the speed and acceleration patterns are different. In the case of Segment A (remaining segments have similar descriptions):

- Sub-segment A1: Vehicle decelerates to negotiate the circulating area of RBT1 and then accelerates as it is leaving the roundabout (deceleration/acceleration pattern);
- Sub-segment A2: Vehicle accelerates after exiting the roundabout back to cruise speed (acceleration only);
- Sub-segment A3: Vehicle drives at cruise speed without significant acceleration or deceleration rates (constant speed);
- Sub-segment A4: Vehicle starting to decelerate while approaching the next roundabout (deceleration only).

The sub-segments A1, B1 and C1 corresponded to the downstream influence of each roundabout, and B4 and C4 corresponded to the upstream influence of each roundabout. Midblock sub-segments are associated to the sub-segments A3 and B3. For the purpose of analysis and supported by empirical measurements, the downstream, midblock and upstream sub-segments will be assumed to be equal in length.

Roundabouts Influence Area (RIAs) is defined as the roundabout circulating area and any upstream and downstream distance needed for deceleration/acceleration from/to free-flow speed (unimpeded speed) through the corridor. 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 get a chance to reach free-flow or cruise speed (sub-segment A3). Therefore sub-segment A3
might not be available for some parts of a roundabout corridor and such design characteristic has an impact on vehicle speed profile and therefore emissions.

**Figure 2**: Segments and sub-segments definition of a roundabout corridor and illustrative speed profile.

### 3.1.1.2. Development of models

From the literature, it is clear that there is a lack of numerical models that are able to quantify emissions at corridors with roundabouts. The existing models (41, 44) were developed for single-lane and multi-lane roundabouts at isolated intersections. Although methodologies of above studies are generalized to estimate the footprints of emissions at roundabouts, its application cannot be extended to corridors. This is mostly due that only traffic data related to the sub-segments B4 (upstream), C1 (circulating area) and C2 (downstream) is considered. Even if proposed methodologies were applied for each roundabout in the corridor, the contribution of sub-segment B3 (mid-block) would not be included.

It must be also taking into account that above methodologies assumed that vehicles reached cruise speed as they exit the roundabouts. However, the vehicle’s speed in several mid-blocks sub-segments can be lower than free-flow speed (e.g. C3), especially in the situation of closely spaced roundabouts. Another consideration that must be mentioned regards the number of circulating lanes of roundabouts and the number of approach lanes of approach roadways between adjacent roundabouts. There are two possible corridors layouts: 1) one
Interpreted modeling for safety and emissions at roundabouts in corridors

with only single lane roundabouts and one approach lane between connection roads and 2) one with a mix of multi-lane roundabouts and single lane roundabouts and approach roads with one or more lanes. Accordingly, two different numerical models are needed to characterize those situations.

This task will be focused on the development of such models that can estimate vehicular emissions for vehicles that drive through the corridor based on speed profiles occurrences (no stop, stop once and multiple stops) and traffic operation. It is well known that these proportions are found to be dependent on the prevailing levels of congestion, simply expressed as the sum of the approach and conflicting flow rates (41). Considering to the roundabouts installed along corridors, one must be considered not only all movements from remaining entry legs but also all conflicting flow rates from each one of approach lanes.

In summary, this task will be composed by four main steps:

1. To quantify traffic and emissions impacts of corridors with only single-lane roundabouts in urban and rural corridors;
2. To identify the different speeds profiles that vehicles can experiences as they drive through the corridor;
3. To explain the interaction between roundabout system operational variable, mainly the approach entry volumes, conflicting or circulating volume and geometry of the roundabout, and the resulting vehicle emissions;
4. Repeat the steps 1, 2 and 3 for corridors with multi-lane roundabouts and more than one approach lanes.

In summary, this task is an empirical approach founded on field measurements of driver and vehicle characteristics. A review of the methodological steps is exhibited in Figure 3.

A wide range (between 5 and 10 corridors) of geometrics and traffic data must be obtained for different roundabouts corridors in order to cover different geometric and operation features. Furthermore, the effect of pedestrians, presence of striping on the roadway, lane configuration, vertical geometry and spacing between adjacent roundabouts along the corridor should be noted. The observational data will be obtained from video files. Each vehicle will be tagged using specific software and the following information will be captured: vehicle type, entry lane, destination lane and timestamp at different instants. In the case of minor vehicles, parameters like arrival and entering times (to obtain gap acceptance and follow-up data) will be recorded and also when crossing a specific section on the approach lane (to obtain delays). Concerning vehicles on major streams, times on conflicts points and upstream and downstream areas will be obtained in order to study the yielding process in the circle.

It should be emphasized that a similar methodology will be also carried out at corridors with traffic signals.
Interpreted modeling for safety and emissions at roundabouts in corridors

3.1.2. Microscopic simulation platform of traffic, emissions and safety

The core of the proposed methodology is to develop a microscopic simulation platform of traffic, emissions and safety. This platform allows assessing corridors with roundabouts impacts on traffic performance, emissions and safety. Figure 4 illustrates the modelling framework.

Firstly, the traffic model is presented (see section 3.1.2.1.) followed by the data collection on each selected study case (see section 3.1.2.2.). After that, the emission (see section 3.1.2.3.) and safety (see section 3.1.2.4.) models are described. Lastly, detailed description of the calibration and validation procedures is made (see section 3.1.2.5.).
Figure 4: Methodological simulation framework of the modelling platform.
3.1.2.1. Traffic Modeling

The increasing of computing performance has yielded an increased use of microscopic traffic models in both environmental and safety fields. Specifically, these models allow exporting the vehicle position and vehicle dynamics data (acceleration/deceleration and speed) second-by-second that provides accurate emissions and relevant safety measures estimation. Note that their simulation outputs as speed and acceleration/deceleration can be employed in instantaneous emission and safety models. These models can be used to assess the environmental and safety impacts of different traffic management strategies applied to the road network traffic, such as, route diversion, variable speed limits or traffic signal coordination (69). In Fontes et al. (70) a review of important research on this topic is presented. Two procedures are usually adopted: 1) a traffic model linked with an external emission model or 2) the emission model which are included in the traffic model. Despite the fact microscopic simulation models have been identified as having potential for emissions evaluation, there are few studies reported their capabilities to capture the real-world vehicle power distributions.

The VISSIM traffic model will be used to simulate traffic operations at corridors with roundabouts and traffic signals (71). This microscopic traffic model is chosen because of the possibility to define and use different road-user behavior parameters and sub-models (car-following, gap-acceptance, lane change) for different traffic controls modelling. VISSIM is widely recognized as a powerful tool for roundabout operational analysis since it can be calibrated to match deterministic capacity relationships (e.g. (72, 73)). VISSIM also allows exporting full disaggregated trajectory files that can be used by external applications to assess environmental and safety impacts, as described on the following sections.

By using a vehicle actuated programming, this traffic model provided an accurate representation of the gap acceptance model in intersections. VAP tool also enables VISSIM to simulate programmable traffic actuated signal controls, both phase or stage based. Moreover, other explanations have supported the application of VISSIM in this research:

- The possibility to define different road-user behavior parameters and sub-models such as car-following and gap-acceptance that are essential for roundabouts modeling;
- The possibility to define vehicle performance parameters such as desired and maximum acceleration per vehicle type and class;
- The possibility to record some traffic performance parameters such as delays or vehicle stops per vehicle type and class;
- A Dynamic Traffic Assignment (DTA) that enables users to define routes and origin-destination routes more efficiently;
- The possibility to store different vehicle dynamics data (speed, acceleration) at a high time resolution (until one tenth of a second);
- An Application Programmer Interface (API) that allows users to define added external applications functionality and access objects and data in the model during the simulation process.
3.1.2.2. Data collection
Several inputs are required to the integrate platform of microsimulation. For this process, the following data collection must be provided:

- Traffic counts by vehicle class;
- Pedestrian counts;
- Speed counts;
- Time-dependent origin/destination (O/D) matrices;
- Vehicle dynamics (speed, acceleration/deceleration and road grade);
- Follow-up times by vehicle class;
- Time gap distributions (acceptance and rejection gaps);
- Cycle length and green times (corridors with traffic signals).

Traffic and pedestrian volumes, as well as time-dependent O/D matrices, will be gathered from two video cameras installed at strategic points along the corridors. Time-gap distributions data (gap-acceptance and gap-rejection) and follow-up times for all turning maneuvers will be also extracted from the videotapes. The critical gap is estimated by applying the Raff's method (74).

Data will be collected at morning and evening peak, and off-peak periods over several typical weekdays (Tuesday to Thursday), under dry weather conditions and using different drivers.

A QSTARZ GPS Travel Recorder (75) will be installed at the test vehicle to obtain some of parameters related to the vehicle activity data (instantaneous speed and acceleration/deceleration) and the selected sites characteristics (latitude and longitude). This equipment supports a Smart Log function and includes a vibration sensor to start and stop automatically logging with a preset time schedule, and smartly manage power saving and waypoint “saving”. Moreover, the software supports providing multi-condition settings to customize specific travel record at high time resolutions (second-by-second basis) (75).

Along with the GPS, it is also used a CarChip Pro by Davis Instruments. This On-Board Diagnostic reader is compatible with passenger cars and light duty trucks (76). The car chip records second-by-second vehicle dynamics such as vehicle speeds, distance traveled, acceleration and braking rates. It also records additional engine performance measures such as coolant temperature, intake air temperature or fuel pressure (76).

Over than 100 GPS travel runs for each movement will be extracted and identified for this research. This number of GPS data samples provided a suitable representation of the local traffic conditions.

3.1.2.3. Emissions Estimation
Regarding to the emission calculation, the “Vehicle Specific Power” (VSP) methodology is employed. This microscopic model is based on vehicle speed, acceleration/deceleration and road grade and has proven to be very effective in estimating instantaneous emissions for both gasoline and diesel (38, 39) as well as for transit bused (40). Several motivations have supported the use of VSP
methodology in this thesis. First, VSP can be applied for both US and European car fleet because it includes a wide range of engine displacement values. Second, VSP-based emission model not only has a better estimation of vehicle emissions than a speed-based emission model, but also is capable of reflecting the emission changes under different operating modes (77). Some previous studies have documented the effective use of VSP in analyzing emission impacts at roundabouts (41, 43-45). The VSP values are categorized in 14 modes, and an emission factor for each mode is used to estimate CO₂, CO, NOₓ and HC emissions from Light Duty Diesel Vehicles (LDDV<1.8 L), Light Duty Gasoline Vehicles (LDGV<3.5L) and Light Commercial Diesel Vehicles ((LCDV<2.5L) (30).

Equation 1 provides the VSP calculation for Light Duty Vehicles (LDV) (78):

\[
VSP = v \times \left[ 1.1 \times a + 9.81 \times \sin(\arctan(grade)) + 0.132 \right] + 0.000302 \times v^3
\]  

(1)

Where:
- \( v \) = Instantaneous speed (m/s);
- \( a \) = Instantaneous acceleration or deceleration (m/s²);
- \( grade \) = Road grade (decimal fraction).

These terms represent the engine power required in terms of kinetic energy, road grade, friction and aerodynamic drag (38). VSP values are usually grouped in combinations of 1 kW/ton from -50 to +50. Then, these values are categorized in modes so that each mode generates an average emission rate. Concerning transit buses, VSP is estimated using typical coefficient values and expressed by equation 2 (40):

\[
VSP = v \times \left[ a + 9.81 \times \sin(grade) + 0.092 \right] + 0.00021 \times v^3
\]  

(2)

where:
- \( v \) = Instantaneous speed (m/s);
- \( a \) = Instantaneous acceleration or deceleration (m/s²);
- \( grade \) = Road grade (decimal fraction).

In this case, VSP combinations are grouped in 8 modes that are corresponding to range values from -30 to 30 kW/ton (40). After the VSP value is calculated, the VSP mode is determined by the VSP range. The corresponding modal emission CO₂, CO, NOₓ and HC are then obtained.

To estimate the amount of emissions generated by Heavy Duty Vehicles (HDV), passenger car equivalents (PCEs) values for HDV at roundabouts (79) will be used in this thesis.

An integrated traffic-emission micro simulation platform (built in C#) will be developed by integrating the microscopic traffic simulator VISSIM and the instantaneous emission model VSP.
3.1.2.4. Safety

The main goal of this new safety assessment approach is a software package developed by the Federal Highway Administration (FHWA) (Surrogate Safety Assessment Model – SSAM) (80) that automates traffic conflict analysis by processing vehicle and pedestrian trajectories on a second-by-second analysis. This approach has all the common advantages of simulation (e.g. safety assessment of new facilities before the occurrence of crashes), but also has some drawbacks: current microscopic traffic models are not able to model some crashes types such as sideswipe collisions, head-on collisions or U-turn related collisions (81).

For each interaction, SSAM stores the trajectories of vehicles from the traffic model and records surrogate measures of safety and determines whether or not that interaction satisfies the condition to be deemed a conflict. The research team used the Time-to-Collision (TTC) and Post-Encroachment Time (PET) as thresholds to define if a given vehicle interaction is a conflict and the Relative Speed (DeltaS) and Maximum Speed (MaxS) as proxies for the crash severity. Their definition is posed as follows (81):

- TTC is the minimum time-to-collision for a vehicle pair of both maintained their instantaneous heading and speed. If at any time step the TTC drops below a given threshold (1.5 seconds and 2 seconds, as suggested for vehicle-vehicle (63) and vehicle-pedestrian events (82), respectively), the interaction is tagged as a conflict;
- PET is the time lapse between end of encroachment of turning vehicle and the time that the through vehicle actually arrives at the potential point of collision. If at any time step the PET drops below a given threshold (5 seconds, as suggested for vehicles (83), the interaction is tagged as a conflict;
- MaxS is Maximum of the speeds of the two vehicles involved in the conflict event (MaxS);
- DR is the rate at which crossing vehicle must decelerate to avoid collision;
- DeltaS is the difference in vehicles (or pedestrians) speeds as observed at the instant of the minimum TTC (81).

The size of the surrogates TTC, PET and DR are intended to indicate the severity of the conflict event. This measures how likely a collision would result from a conflict, such that:

- Lower TTC indicates higher probability of collision;
- Lower PET indicates higher probability of collision;
- Higher DR indicates higher probability of collision.

MaxS and DeltaS are used to indicate the likely severity of the (potential) resulting collision if the conflict event had resulted in a collision instead of a near-miss, such that:

- Higher MaxS indicates higher severity of the resulting collision;
- Higher DeltaS indicates higher severity of the resulting collision resulting collision (58).
3.1.2.5. Calibration and Validation

Calibration and Validation procedures are very crucial to make simulation model looks real. Model calibration is defined as the process in which parameters of the traffic model are tuned and fitted so the model will accurately represent field-measured traffic data. Model validation is defined as the process of comparison between traffic data from the model and data collected from the field (84).

In the early research, many authors have used single-criterion methodologies in which the extent of errors between estimated and observed measures such as traffic flows (83), travel time (85) or capacity (85), were minimized. Others have developed microscopic simulation platforms by using multiple criteria measures in which weight summation of each single-criteria was minimized (86, 87). Both single-criteria and weighted summation were shown as inadequate for calibrating microscopic traffic platforms (67) since traffic dynamics is a multi-faceted problem and some trade-offs between criteria can be found. Another method to calibrate traffic models is to regard model calibration as an optimization problem in which several parameters are tested to satisfy the objective function. Nonetheless, the computational complexity arise from this procedure can be exponential (87). In this context, Punzo et al. (88) recommend a selection of a subset of parameters to perform a sensitivity analysis and also to narrow the range of possible values of each parameter. In the context of roundabouts operations, Vasconcellos et al. (89) proposed a method to calibrate the car-following model for the effect of driver variability in the speed-flow relationship. In (90), VISSIM was calibrated using field gaps in two-lane roundabouts.

In this research, the model calibration is focused on the driver behavior parameters of the traffic model, while model validation is related with O-D matrices, travel times and VSP mode cumulative distributions, CO₂, CO, NOₓ and HC emissions, and traffic conflicts. Note that different data samples will be used for calibration and validation procedures.

Calibration of the VISSIM parameters is made by modifying driver behavior and vehicle performance parameters of the traffic model and examined their effect on traffic volumes and speed for each link. The main driver behavior parameters are divided into car-following parameters (average standstill distance, additive and multiple part of safety distance), lane-change parameters, gap acceptance parameters (minimal gap time and minimal headway) and simulation resolution (91).

To optimize the aforementioned parameters, a procedure based on the Simultaneous Perturbation Stochastic Approximation (SPSA) genetic algorithm is used. The objective function, the minimization of Normalized Root Mean Square (NRMS), is denoted by Equation (3).

NMRS is defined as the sum over all calibration periods of the average of the sum over all links of the root square of the square of the normalized differences between observed and estimated parameters (92). The normalization enables the consideration of multiple performance measures, in this case, link volumes, speeds and acceleration/deceleration. The calibration procedure is formulated as follows:
Interpreted modeling for safety and emissions at roundabouts in corridors

\[
NRMS = \frac{1}{\sqrt{N}} \times \sum_{t=1}^{T} (W_1 \times C_1 + W_2 \times C_2 + [1 - W_1 - W_2] \times C_3)
\]

(3)

\[
C_1 = \sqrt{\sum_{i=1}^{I} \left( \frac{v_i - \bar{v}(\theta)}{v_i} \right)^2}
\]

(4)

\[
C_2 = \sqrt{\sum_{i=1}^{I} \left( \frac{s_i - \bar{s}(\theta)}{s_i} \right)^2}
\]

(5)

\[
C_3 = \sqrt{\sum_{i=1}^{I} \left( \frac{a_i - \bar{a}(\theta)}{a_i} \right)^2}
\]

(6)

Subject to:
Lower bound \( \leq \theta \leq \) Upper bound

Where: \( v_i \) = Observed link volumes for link \( i \); \( \bar{v}(\theta)_i \) = Estimated link volumes for link \( i \); \( s_i \) = Observed speeds for link \( i \); \( \bar{s}(\theta)_i \) = Estimated speeds for link \( i \); \( a_i \) = Observed accelerations for link \( i \); \( \bar{a}(\theta)_i \) = Estimated accelerations for link \( i \); \( N \) = Total number of links in the coded network; \( T \) = Total number of time periods \( t \); and \( W_1, W_2 \) = Weights factors used to assign more or less value to volumes, speeds or acceleration based on the trustworthiness of the corresponding data (note \( 0 \leq W_1, W_2 \leq 1 \)).

Considering the calibration criteria, the current accepted practice, as recommended by the FHWA is to rely the Geoffrey E. Havers (GEH) statistic for assessing goodness-of-fit. The difference between observed and estimated link volumes should be less than 5% for at least 85% of the coded links (93).

The model validation is focused on the comparison between estimated and observed O/D matrices, pedestrian volumes and travel times for a preliminary number of runs (between 10 and 20, as suggested by Hale (94)). GEH statistic (93) and Root-mean-square percentage error (RMSPE) (95) will be used as measures of the goodness-of-fit. Along the validation of previous measures, the observed and estimated VSP cumulative probability distributions will be also compared. This validation step allows assessing differences in the acceleration/deceleration profiles between field measurements and simulation.

Since the number of data sets (number of seconds) is roughly higher than 40, two-sample Kolmogorov-Smirnov test (K-S) for a 95% confidence is deemed appropriate to assess if the probability distributions of two samples are different (96). K-S test is recognized to be one of the most useful and nonparametric methods for comparing two samples, as it is sensitive to differences in both location and shape of the empirical cumulative distribution functions of the two data samples. Moreover, it is also suggested when there is a natural ordering of the modes (bins) (97). The resulting estimated \( \text{CO}_2 \), \( \text{CO} \), \( \text{NO}_x \) and \( \text{HC} \) emissions are compared with observed values. Lastly, the simulated conflicts that can be
recorded in SSAM model will be compared by real crash data from a crashes and conflict model for roundabouts.

### 3.1.3. Scenarios evaluation

After developed the modeling platform of traffic and emissions in corridors and traffic signal corridors, several scenarios will be implemented. The main purpose of this task is to understand how emissions and safety performance vary in according to the different traffic conditions.

Thus, the following scenarios will be compared:

1. Different traffic demands (peak and off-peak periods);
2. Different pedestrian flows (peak and off-peak periods);
3. Different traffic signal settings (fixed versus actuated);
4. Reduction of vehicle’s speed.

The emissions and safety performance of each scenario will be evaluated in terms of: a) Overall roundabouts corridor vs. Overall traffic signal corridor, and b) Overall roundabouts corridor vs. individual roundabout along the corridor.

### 3.1.3. Multi-objective analysis

This section gives a brief description of the multi-objective optimization task proposed in this research, which includes the formulation of the multi-objective optimization (see section 3.1.3.1.) and the selected algorithm (see section 3.1.3.2.) to solve its solution.

#### 3.1.3.1. Micro simulation optimization formulation

Multi-objective optimization is concerned with the solution of problems with multiple, often conflicting, criteria. In particular, the optimization problem consists of maximizing or minimizing a function by choosing different input values from a set of available alternative. The challenge regarding the application of this approach is that, instead of a unique optimal solution, multi-objective optimization results in several solutions with different trade-offs among criteria. Thus, a Decision Maker is needed to provide useful information and also to identify the most acceptable solution.

The general multi-objective optimization problem is posed as follows (see Equations 7, 8 and 9)

\[
\min \ F(x) = [f_1(x), f_2(x), \ldots, f_m(x)]
\]

Subject to

\[
g_i(x) \leq 0, \quad i = 1, 2, \ldots, I
\]

\[
h_j(x) \leq 0, \quad i = 1, 2, \ldots, J
\]
In which: \( f_1(x), f_2(x), \ldots, f_m(x) \) are the \( m \) objective functions, \( i \) is the number of inequality constraints, \( j \) is the number of equality constraints, \( X = \{ x_1, x_2, \ldots, x_n \} \) is a \( n \)-dimensional design variables vector in the solution of space \( X \).

For a multi-objective optimization problem, any two solutions \( x_1 \) and \( x_2 \) can have one of two possibilities: one dominates the other or none dominates the other. In a minimization problem, without loss of generality, a solution \( x_1 \) dominates \( x_2 \) if the following two conditions are satisfied (see Equations 10 and 11):

\[
\forall i \in \{ i = 1, 2, \ldots, m \} : f_i(x_1) \leq f_i(x_2)
\]

\[
\exists i \in \{ i = 1, 2, \ldots, m \} : f_i(x_1) < f_i(x_2)
\]

If both conditions are satisfied, the solution \( x_1 \) does not dominate the solution \( x_2 \). If \( x_1 \) dominates the solution \( x_2 \), \( x_1 \) is called the nondominated solution within the set \( \{ x_1, x_2 \} \). This means that there exists no feasible solution \( x \) that can decrease some objective functions without causing at least one other objective function to increase.

The set of all possible solutions that are nondominated within the entire search space is denoted as Pareto-optimal set. Concerning the respective objective function values in the objective space, they are defined as the Pareto front. It should be mentioned that, in some situations, the number of Pareto optimal solutions can be infinite. Hence, the multi-objective optimization must include a practical approach to identify a set of solutions, called as the best-known Pareto set so that it can be suitably represented as the Pareto optimal set.

In summary, the multi-objective optimization should be achieve the following goals (98):

1. The best-known Pareto set must be as near as possible to the true Pareto set;
2. The solutions in the best-know Pareto set must be diverse in relation to the Pareto front as well as uniformly distributed in order to assure a faithful representation of trade-offs;

The best-known Pareto front should be extended at both ends in order to explore extreme solutions.

3.1.3.2. Genetic Algorithms

The issue of finding an optimal solution design is frequently discussed in the transportation research area. Among the set of search and stochastic optimization techniques, Evolutionary Algorithms (EAs) have recently received increased interest. Several authors recognized merits of their applications in solving real-world multi-objective problems (99, 100). There have been three main independent implementation instances of EAs (101): Genetic Algorithms (GAs) (102, 103), Evolution Strategies (ESs) (104) and Evolutionary
Programming (EP) (105). Each approach is inspired by the same basic mechanisms of natural evolution: selection, mutation and crossover.

The GAs are often used to represent EAs. These adaptive meta-heuristic search techniques are based on the mechanism of natural selection and natural genetics that potentially guarantees a robust search, and also a near-optimal. This means that neighborhood solutions from an initial incumbent solution (value of the objective function for the problem being solve that is worse than the optimal objective function value) is allowed to move in the direction of the worse objective (103). The GAs can deal successfully in a wide range of problem areas, which include multi-modal objective problems, differentiable and non-differentiable functions, discrete and continuous parameters, as well as problems with convex and non-convex feasible regions (102, 106). GAs have been also widely employed in multi-objective optimization studies applied in the transportation field such as traffic signal optimization (107-111), scheduling problems (112), traffic routes assignment (113), network design problems (114-118), road-bicycle lanes network problems (119), and crash safety design (120).

The first multi-objective GA, called Vector Evaluated Genetic Algorithms (VEGA), was proposed by Schaffer, in 1985 (121). Afterwards, various multi-objective genetic algorithms were developed: Multi-Objective Genetic Algorithms (MOGA) (122), Weight-Based Genetic Algorithms (WPGA) (123), Random weighted genetic algorithms (RWGA) (124), Niched Pareto Genetic Algorithms (NPGA) (125), Nondominated Sorting Genetic Algorithm (NSGA) (126), Fast non-dominated sorting genetic algorithms (NSGA-II) (127), and Rank-Density Based Genetic Algorithm (RDGA) (128). The main differences of above-mentioned GAs are related to their fitness assignment method, elitism and diversification approaches.

Among previous multi-objective GAs, the NSGA-II will be adopted in this research. Several explanations have supported NSGA-II used: a) diversity in optimal solutions by incorporating the crowding distance into the fitness function and b) a binary tournament approach that provides accommodate the selection process (127). In contrast to the conventional GA(s) based methods, NSGA-II not require weighting factors for conversion of multi-objective function into an equivalent single objective function. Moreover, NSGA-II has been tested many times in the research field of evolutionary optimization so that it has well-known to find a good approximation of an optimal Pareto front (129). The main disadvantage of NSGA-II is that the crowding distance only works in the objective space (129). A good deal of research can be found in the transportation field in which NSGA-II has been used, namely in network design problems (114, 118), traffic signal optimization (108), crash safety design (120) and in the calibration of microscopic traffic models (67).

The main feature of NSGA-II is the implementation of a fast non-dominated sorting procedure. Specifically, this approach incorporates elitism, and then the fitness sharing function is replaced by a crowded-comparison approach that eliminates, either the dependence of fitness value to yield performance of sharing function, and the overall complexity of the process (127).
In order to sort a population according to the level of non-domination, each solution is compared with every other solution in the population. This requires \( n \times m^2 \) comparisons for each solution while, for NSGA, the complexity of nondominated sorting is \( n \times m^3 \). NSGA-II also implements elitism for multi-objective search by storing all non-dominated solutions found so far, beginning from the initial population. Accordingly, the convergence properties towards the true Pareto-optimal set are improved (127).

The diversity and the spread of solutions are guaranteed without the use of sharing parameters since NSGA-II adopts a suitable parameter-less niching approach. It is then used a crowding distance, which estimates the density of solutions in the objective space, and also a crowded comparison operator, which conducts the selection process towards an uniform spread Pareto front. Note that both discrete (binary-coded) and continuous (real-coded) are allowed to be used by NSGA-II (127). More information about NSGA-II procedure and its basic theories, such as selection, crossover, and mutation can be found elsewhere (127).

**Figure 5** shows the NSGA-II main steps.

NSGA-II will be implemented in Matlab. A user pre-specified maximum number of generations is defined as the stopping (convergence) criteria of the NSGA-II procedure. Unlike single objective optimization, where a simple convergence criterion is sufficient to assess the performance, the multi-objective optimization results must be assure both the convergence to Pareto Optimal Front (POF) and the diversity of the solutions (130).

The convergence to POF is based on the comparison among the sets of non-dominated solutions from various generations. The smaller the number of dominated solutions, the better is the convergence. Concerning the diversity of the solutions, it is measured by the estimating of the Spread and the Uniformity Measure metrics. The spread of the front is calculated as the diagonal of the largest hypercube in the function space that encompasses all solutions points. A large spread is desired to find diverse trade-off solutions. The Uniformity Measure identifies the presence of poorly distributed solutions by estimating how uniformly the points are distributed in the POF. This measure it is estimated from the standard deviation of the crowding distance (130).

Initially, the maximal number of generations will be set to 3000 for all the test instances while the crossover and mutation rates will be set at 90% and 10%, respectively. Each scenario will be run 20 times in the NSGA-II code. For each repetition, above performance metrics (Number of dominated solutions, Spread and Uniformity Measure) are computed. Once guaranteed the convergence to POF and the diversity of the solutions in all scenarios, an equal maximum number of generations will be employed in each scenario.
Figure 5: Basic structure of NSGA-II algorithm.
4. Results

This section presents some preliminary results regarding the data collection and emissions calculations taken at two corridors with roundabouts located in US.

First, the introduction and main objectives are presented (see section 4.1.). After that, the selected corridors and data collection procedures are introduced (see section 4.2.), followed by the main results and its discussion (see section 4.3.). Finally, the main conclusions are exposed (see section 4.4.)

4.1. Introduction and objectives

This study provides a methodology to quantify and characterize the vehicular emissions of roundabouts at a corridor level by dividing the corridor into multiple segments (upstream of each roundabout, circulating area, downstream of the roundabout as well as midblock sub-segments between adjacent roundabouts). The main goal of the methodology is to identify the locations along the corridors where the emissions tend to be consistently high. These locations are called emissions hotspots. The methodology is then applied to two roundabout corridors located in San Diego (California) and Avon (Colorado) in the United States.

Thus, the main objectives are:

- To analyze the vehicular emissions for each pair of roundabouts throughout the corridor;
- To identify locations with the highest amount of emissions generated (hotspots) as the vehicle drives through the corridor.

4.2. Selected corridors and field measurements

Figure 6 displays an aerial view of the data collection sites investigated in this study as well as segments and sub-segments identification for north-south and south-north directions, based on definitions shown in Figure 2.

One of the study locations is in San Diego, California, along La Jolla Boulevard Figure 6-a). The free-flow speed is fairly constant along this corridor, and the spacing is approximately equal between the five roundabouts (coefficient of variability of average spacing is 0.10). The second corridor is located in Avon, Colorado, along Avon Road. The spacing between the roundabouts is not uniform (coefficient of variability of average spacing is 0.46).

La Jolla corridor is 966 meters long, including five single-lane roundabouts in an urban environment. The Avon corridor is 805 meters long, and it includes three two-lane roundabouts and a tear drop interchange with two single-lane roundabouts. The RBT3 and RBT4 roundabouts are located in a close proximity to each other and therefore make the case for overlapping RIAs for this corridor. The posted speed limit is 25 mph for both corridors.

Additionally, sites characteristics such as location, inscribed circle diameters, entry deflection angle, distance between two adjacent roundabouts (measure
Interpreted modeling for safety and emissions at roundabouts in corridors

from the upstream yield lane) and some descriptive statistics are summarized in Table 2. Free-flow speeds and traffic data information are also provided.

Figure 6: Aerial View of the Two Data Collection Roundabouts Corridors and segments identification (black color-North-South; red color-South-North): a) La Jolla; b) Avon (Source: http://www.arcgis.com).

For vehicle activity characterization, the authors used second-by-second vehicle dynamics data. A Light Duty Gasoline Vehicle (1.5<LDGV<2.5L) was used in order to conduct several runs through the corridors. These runs were performed during morning, evening and off-peak periods (from 7 AM to 7 PM). The research team scouted and collected data at the two selected corridors in the fall of 2013. A QSTARZ GPS Travel Recorder (75) 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). 70 GPS travel runs for the two directions of through movements are analyzed for this research (total of 280 speed profiles).
Interpreted modeling for safety and emissions at roundabouts in corridors

Table 2: Key characteristics of selected corridors

<table>
<thead>
<tr>
<th>Site</th>
<th>ID</th>
<th>Number of circulating lanes</th>
<th>Inscribed Diameter [m]</th>
<th>Central Island [m]</th>
<th>Legs</th>
<th>Entry deflection angle (North-South/South-North)</th>
<th>Distance from upstream Roundabout [m]</th>
<th>Average roundabout spacing [m]</th>
<th>CV</th>
<th>Measured Arterial Volume (7 AM - 7 PM)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>North South South North</td>
</tr>
<tr>
<td>La Jolla</td>
<td>RBT1</td>
<td>One</td>
<td>25</td>
<td>16</td>
<td>4</td>
<td>30°/31°</td>
<td>–</td>
<td>218.8</td>
<td>0.10</td>
<td>5,531 5,688</td>
</tr>
<tr>
<td></td>
<td>RBT2</td>
<td>One</td>
<td>24</td>
<td>15</td>
<td>4</td>
<td>29°/30°</td>
<td>248</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>RBT3</td>
<td>One</td>
<td>25</td>
<td>14</td>
<td>4</td>
<td>34°/29°</td>
<td>227</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>RBT4*</td>
<td>One</td>
<td>22/25</td>
<td>15/19</td>
<td>4</td>
<td>22°/31°</td>
<td>192</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>RBT5</td>
<td>One</td>
<td>24</td>
<td>15</td>
<td>3</td>
<td>32°/31°</td>
<td>208</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Avon</td>
<td>RBT1**</td>
<td>Two</td>
<td>42</td>
<td>24</td>
<td>3</td>
<td>20°/-</td>
<td>–</td>
<td>197.0 (-10%)</td>
<td>0.46</td>
<td>6,240 6,201</td>
</tr>
<tr>
<td></td>
<td>RBT2**</td>
<td>Two</td>
<td>48</td>
<td>28</td>
<td>3</td>
<td>28°</td>
<td>144</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>RBT3</td>
<td>Two</td>
<td>46</td>
<td>23</td>
<td>4</td>
<td>23°/30°</td>
<td>170</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>RBT4</td>
<td>Two</td>
<td>45</td>
<td>28</td>
<td>4</td>
<td>34°/42°</td>
<td>124</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>RBT5</td>
<td>Two</td>
<td>44</td>
<td>26</td>
<td>4</td>
<td>39°/38°</td>
<td>350</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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

**Roundabouts 1 and 2 are tear drop interchange roundabouts.

Notes: CV – Coefficient of Variability (ratio between average roundabout spacing and standard deviation of average roundabout spacing)
4.3. Discussion and Results

In this section, the main results from characteristics speed trajectories (see section 4.3.1.), acceleration/deceleration profiles (see section 4.3.2.), sub-segments emissions (see section 4.3.3.) and emissions per unit distance (see section 4.3.4.) were presented and discussed.

4.3.1. Characteristic Speed Trajectories

Figure 7 (a-d) depicts the speed trajectories through La Jolla and Avon corridors. The speed profiles across La Jolla corridor were similar as verified in Figure 2. This mean that vehicles accelerate to free-flow upon exiting each roundabout (sub-segments B2, C2, D3 and E2) as they approach each mid-block areas (sub-segments B3, C3, D3 and E3). Nonetheless, vehicles speeds in sub-segments B3, C3, D3 and E3 are lower than free-flow speeds. Specifically, vehicles reached a 40km/h of maximum speed on those sub-segments while outside corridor the speed increased up to 55km/h. It was also verified that, in mid-block sub-segments, vehicles tend to circulate at nearly constant speeds since adjacent roundabouts were fairly spaced (see Table 2). Similar results were found in the opposite through movement (see Figure 7-b).

The results from the Avon corridor analysis (see Figure 7c-d) showed that the highest average speeds occurred at the RBT4 and RBT5 roundabouts (sub-segments E2 and E3 in North-South direction, and B2 and B3 in South-North direction). This was explained by the distance between those roundabouts which was over than 300 meters and enables vehicles to attain free-flow speeds. On the remaining roundabouts, the speed values were not so sharper. This was particularly true between RBT3 and RBT4 whose distance was about 59 meters. It was also found that the overlapping of RIA was notably expressive between RBT3 and RBT4. Therefore, vehicles maximum speed at D3 (see Figure 7-c) and C3 (see Figure 7-d) was half of than the observed at the sub-segments E3 (see Figure 7-c) and B3 (see Figure 7-d).
Figure 7: Speed trajectories by distance travelled for each through movement by corridor: a) La Jolla (North-South); b) La Jolla (South-North); c) Avon (North-South); d) Avon (South-North).
4.3.2. Characteristic Acceleration and deceleration Trajectories

The acceleration and deceleration cycles for vehicles that are crossing the selected studied corridor are depicted in Figure 8 (a-b) for both through movements. The higher acceleration rates in La Jolla corridor were recorded over the circulating area of roundabouts (sub-segments B1, C1, D1 and E1). The experimental measurements also indicated that the deceleration of vehicles increased when vehicles approaching each one of the roundabouts (B4, C4, D4 and E4). From the Figure 8 (a-b), and as suspected, the lowest acceleration and deceleration rates were achieved at the mid-block sub-segments in which vehicles drove near the cruise speeds. In summary, the acceleration/deceleration cycles did not significant different between each pair of roundabouts. Several explanations supported these results. First, the distance between consecutive roundabouts is similar across 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 2).

Concerning the Avon corridor, it was noted that, between RBT3 and RBT4 (overlapping of RIAs), vehicles suffered the highest acceleration and deceleration through the corridor as seen in Figure 8 c-d. In particular, both accelerations and decelerations range from -3 m/s² to 3 m/s². It should be mentioned that vehicles also tend to decelerate faster before RBT2 (North-South direction) that is placed in Rain drop interchange area. This means that after B3 sub-segment vehicles still driving on free-flow speed and decelerate approximately 50 meters before C1 (circulating area of RBT2) as shown in Figure 8-c. The values of deceleration obtained for vehicles approaching RBT3 and RBT4 were also expressive. Note that these roundabouts are the fairest spaced along the corridor.
Interpreted modeling for safety and emissions at roundabouts in corridors

**Figure 8:** Acceleration/Deceleration cycles by distance travelled for each through movement by corridor: a) La Jolla (North-South); b) La Jolla (South-North); c) Avon (North-South); d) Avon (South-North).
4.3.3. Segments and Sub-segments Emissions

Figure 9 a-b illustrates that the highest amount of CO$_2$ emissions per vehicle, about 36% of the total emissions in the 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. Because of the large distance between the roundabouts, the vehicles often reach the cruise speed in the midblock section (A3, B3, C3 and D3) as they leave one roundabout RIA and travel toward the adjacent RIA. Consequently, sub-segments A4, B4, C4 and D4 (upstream) contribute to more than 27% of total emissions in the corridor (they include about 29% and 30% of travel distance and travel time, respectively). These analyses suggest that the deceleration from cruise speed to the circulating speed is especially relevant for CO$_2$ 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 emission is about 24% for both through movements). This is due to the smooth speed profiles at those locations. Regarding the assessment of each pair of roundabouts across the corridor, that is, segments A, B, C and D, the findings point to small differences in emissions. Specifically, CO$_2$ emissions contributions of each segment range from 23% to 25% for segments C and A, respectively. 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 2 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 9 c-d, vehicles emit about 30% of CO$_2$ in 25% and 23% of travel distance and travel time respectively on both directions. Similarly, sub-segments A1, B1, C1 D1 and E1 have a significant effect on CO$_2$ emissions along that corridor. Their contribution is about 26%, on 23% of travel distance. This is mostly because of the high inscribed diameter at those roundabouts. The results also show that due to different lengths of each segment there is a difference in emissions for each pair of roundabouts. From Figure 9 c-d, and as suspected, the highest amount of overall CO$_2$ emissions is produced between RBT4 and RBT5 roundabouts (Segments D and A on north-south and south-north movements, respectively). For that location, a contribution of more than 43% of total emissions represents 42% of the travel distance is observed, which is consistent. Along the tear drop interchange, on segment A (north-south movement), there is no substantial impact of CO$_2$ emissions when compared with Segments B and D. CO$_2$ emissions only represent 19% of total emissions of the corridor. Note that vehicles travel 18% of distance on that segment. Similar results are found on the opposite through movement.
4.3.4. Emissions per unit distance

Figure 10 a-d illustrates the CO₂ emissions per unit distance by sub-segment and regarding the overall corridor. The figure shows that 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. These results are verified on both through movements. In particular, above sub-segments generate an average CO₂ emissions per unit distance higher than 27% (210 g/km – north-south) and 33% (218 g/km – south-north) to the averages values of the corridor (165 g/km and 164 g/km on north-south and south-north directions, respectively). It is also observed that the CO₂ emissions per unit distance in some circulating sub-segments are higher than averages values which are recorded in both movements. On average, CO₂ emissions per unit distance at the circulating sub-segments (A1, B1, C1, D1 and E1) are higher by 3% (170 g/km) and 10% (179 g/km) over the average value which is recorded in north-south and south-north movements, respectively. It should be emphasized that when vehicles are crossing each pair of roundabouts, emissions per unit distance follow a similar trend. Taking as an example the 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 yet again, they increase on sub-segment A4 (see Figure 10 a-b). A2 and A3 are related to the highest and lowest emissions per unit distance across the roundabouts corridors.
distance sub-segments, respectively, within Segment A. In some segments, the differences between above sub-segments exceed the 95 g/km.

The analysis results show that the emissions hotspots in the Avon corridor, 23% higher than the average corridor value (≈167g/km), are generated in the circulating areas of the roundabouts (A1, B1, C1 and D1). Concomitantly, vehicles at any downstream sub-segments generate an amount of CO\(_2\) emissions per unit distance higher than the average value of the corridor with 19%. The effect of tear drop interchange on the north-south direction (Segment A) is also relevant (average CO\(_2\) emissions per unit distance of 185 g/km in 18% and 17% of the total distance and time, respectively) as shown in Figure 10-c. This is mostly due to the higher speeds (cruise speed) in almost Segment A length between RBT1 and RBT2. Unlike tear drop interchange, Segments C and D on north-south and south-north, respectively, generate an amount of CO\(_2\) emissions per unit distance 6% and 3% below the average value of the Avon corridor. The findings for closely spaced roundabouts (RBT3 and RBT4), as illustrated in Figure 10 c-d, prove that CO\(_2\) emissions per kilometer travelled at the downstream and mid-block sub-segments are much smaller than those which are observed in equivalent sub-segments Since vehicles have not enough distance to attain free-flow speeds, lower acceleration rates are observed at the downstream sub-segment in comparison to the equivalent segments.

![Figure 10](image_url)

**Figure 10:** CO\(_2\) Emissions (g/km) per unit distance for each sub-segment across the roundabouts corridors and overall corridor: a) La Jolla (North-South), b) La Jolla (South-North); c) Avon (North-South); d) Avon (South-North).
4.4. Conclusions

It was found that the emissions distributions along the corridor with fairly spaced roundabouts and enough spacing to attain cruise speed over the mid-block was similar in 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 35 %) both in absolute terms and per unit distance. Considering the corridor with evenly spaced roundabouts, the emissions hot spots per unit distance, about 23% higher than the average corridor value, were located at the circulating areas sub-segments. This was particularly true for closely spaced roundabouts (~100 meters of spacing) in which vehicles decelerated after the roundabout exit section (at the downstream sub-segment).
5. **Papers in Publication**

During the first year of Doctoral grant the candidate was co-author of several papers.

5.1. **Papers published (or accepted for publication) in scientific journals**


3. Jorge Bandeira, Paulo Fernandes, Tânia Fontes, Sérgio Ramos Pereira, Asad J. Khattak & Margarida C. Coelho, Assessment of Eco Traffic Assignment Strategies in an Urban Corridor, accepted to be published in the Special Issue for Transportation Research – Part C on Advanced Road Traffic Control, in press.


5.2. **Book Chapters**

5.3. Conference proceedings


3. Bandeira, J.M., Fontes, T., Pereira, S.R., Fernandes, P., Khattak, A.J., Coelho, M.C. Assessing the importance of vehicle type for the implementation of eco-routing systems, Accepted to be presented in the 17th meeting of the EURO Working Group on Transportation - EWGT 2014, to be held in Seville, July 2014.


URL: http://10cna.web.ua.pt/


URL: http://www.ewgt2013.com/1%2009%202013_Programa%20formatado.pdf
6. Future Tasks

The following tasks are expected to be developed during the second year of this doctoral research (1st of June 2014 – 31st of May 2015).

- Compare the results obtained in US corridors with Portuguese corridors with similar design features (equally spacing vs. unequally spacing; traffic flows);
- To explore pedestrian crosswalk locations effect in some of these corridors on traffic performance and emissions using a microsimulation approach as well as a multi-objective optimization;
- To developed regression models to predict the relative occurrence of speed profiles (no stop, stop once and several stops) in corridors based on traffic flows data (corridors);
- To compare performance and emissions impacts of corridors and traffic signals in corridors using a microsimulation approach.

6.1. Papers in preparation


Acknowledgments

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Interpreted modeling for safety and emissions at roundabouts in corridors

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79. Lee C. Passenger Car Equivalents for Heavy Vehicles at Roundabouts: Estimation and Application to Capacity Prediction. Accepted for presentation in the 93rd Annual Conference of the Transportation Research Board; 2014 January 12-16; Washington, D.C., United States.


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