Interpreted modeling for safety and emissions at roundabouts in corridors

Projeto de Tese I

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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 between different roundabouts in corridors with respect to emissions and safety. To achieve the proposed objectives, several roundabouts corridors will be analysed using empirical approaches, as well as traffic and emission models. Crashes prediction models will be also developed taking into account parameters that influence the road safety of those facilities. Using multi-objective analysis, this work will expect to identify the most optimized traffic system both in terms of emissions and safety.

This work plan presents a review of the technical literature, sets the main motivations of this thesis topic, and highlights the objectives and the structure of this research.
1. Introduction

1.1. General Statement of the Problem

Roundabouts are proven to be a safety countermeasure for intersections. Roundabouts reduce the unnecessary number of stops for vehicles compared to stop-controlled intersections. Compared to stop-controlled intersections, roundabouts also improve the capacity of intersection. Roundabout design imposes different driver behaviors compared to signalized or stop-controlled intersections. Roundabout design causes drivers to lower their speed and decelerate as they approach the roundabout and enter the circulating traffic and accelerate as they exit the circulating traffic. Roundabout operation is effected 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, emissions and safety.

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 road safety 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 (CO$_2$), carbon monoxide (CO), nitrogen oxides (NO$_X$) and hydrocarbons (HC) emissions;
2. To improve crashes predicting models for urban and rural corridors with roundabouts that cover different traffic characteristics and design features of those facilities;

3. To compare corridors with roundabouts in safety and emissions from well-characterized scenarios according to the Portuguese reality;

To perform a multi-objective analysis to identify the most optimized traffic system both in terms of traffic performance, emissions and safety.

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 [1]. Since the adoption of a yield-at-entry regulation in 1966 in Great Britain [2], roundabout design has evolved from the use of larger circles with emphasis on merging and weaving to small compact roundabouts.

From that point on, there has been high interest and significant research on roundabouts because of the simplicity in their design, operations and safety [3]. These traffic facilities provide higher capacity levels in intersections compared to stop-controlled intersections [4] and are most robust concerning to the reduction of the unnecessary number of vehicle stops [5]. The empirical delay formula for roundabouts in the Highway Capacity Manual [5] 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 [6]. 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 [4].

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. They usually require drivers to perform continuous acceleration-deceleration cycles. One 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 pollutants emissions, namely in urban and rural areas.

From the literature review, it is clear that there is a lack of research to demonstrate the benefits of corridors with roundabouts in the field of emissions and safety as well as on their comparison to other forms of intersection. The few
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studies carried out in corridors raise some uncertainties about their effectiveness. Hallmark et al. [7] recorded marginal benefits in improved traffic flow of roundabouts within signalized corridors over stop and signal control intersections. In [8], 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 [7, 8] 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 [9]. 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.

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 [10]. 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 [10]. The LR942 Linear Regression Model [11], French Girabase Model [12] or based on Neural Networks are the well-known empirical regression models [13].

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 [10]. 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 [14]. 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 [15] 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 [5] 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 [10]. Nonetheless, it is recognized that they still require more improvements. First, the limited priority process in roundabouts is rarely included [16]. Second, it is demonstrated that pedestrian’s crossings have effects in the capacity of entry and exit sections of the roundabouts [17]. Third, there is a lack of reliable estimations about some of parameters that are present in most gap-acceptance formulas [18]. 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 [10].

A good deal of research, in which the simulation was applied to assess capacity of roundabouts, can be found elsewhere [17, 19-21].

In [19], 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 [20]. Bastos Silva and Vasconcelos [17] 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 [21], 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 [22], MOBILE6 [23] or TREM [24]), mesoscopic (e.g. TEDS [25]), and microscopic (VT-MICRO [26], CNEM [26], VSP [27] and MOVES [28]) emission models, their applications on roundabouts case studies are very limited. COPERT [22] and MOBILE6 [23] models, for instance, are not recommended in micro scale impact of corridors with traffic interruptions (e.g. pay tools, roundabouts) [29, 30] 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 pollutants emissions. Nevertheless, the impact of each stop and go cycles are not taken into account [9]. Traffic and Emission Decision Support (TEDS) model can be applied in urban corridors, but only single lane roundabouts are included in this analysis [25].

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) [26]. 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 [26]. The Motor Vehicle Emission Simulator (MOVES) [28] 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. [23, 27] 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 [31, 32] as well as in transit buses [33]. 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. [34, 35]) and in Europe (e.g. [34, 36-38]).

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 [34-37, 39, 40], only field data was used; in the second group [38, 40-43], a microscopic traffic model was linked with an external emission model.
The research of Coelho et al. [34] and Salamati et al. [37] should be highlighted. Coelho et al. [34] 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. [37] 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 [39], 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 NO\textsubscript{X}, respectively. Rakha et al. [44] 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. [36] 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. [35] 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. [41] 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. [42] 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. [43] 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 [40] 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$_2$, CO, NO$_X$ and HC, compared to other alternatives. Vasconcelos et al. [38] 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$_2$ and NO$_X$ 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 researcher’s findings were not conclusive 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 [45, 46].

2.3.3. Safety

Although the mostly of crashes at roundabouts results in property damage only [47], there are an extensive body of research focus on demand and improvement of crash models [4, 48-50] applied to roundabouts and intersections.

Dijkstra et al. [51] 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. [21] performed an exhaustive analysis of roundabout crash patterns in the United States (US) and developed a method to calculate crash type percentages. In [52], 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) [53] 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. [54] 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. demonstrated that the simulated conflicts were not good indicators.
for the traffic when the conflicts were generated by unexpected driving manoeuvres (e.g. illegal lane-change) [55]. Some authors suggested specific procedures to calibrate and validate simulation models for safety assessment but this is still an ongoing research field [56, 57].

2.4. Summary of literature review and motivations

From above-mentioned studies, some gaps in the research were observed:

- The assessment of the environmental and safety of roundabouts in a series 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 pollutants 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 study seeks to contribute to a methodology that can incorporate the corridor geometric features and traffic stream characteristics to assess safety and emissions. This methodology can be useful to the local authorities to the support of decisions in the field of safety 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 Portugal-based scenarios. The integration of three areas on those uninterrupted flow facilities is worthy of research and analysis at this stage.
3. Methodology

The research work plan consisted of six interrelated tasks:

- **Task 1: Selected data from Police Road Accidents.**
  The purpose is to set a database of geometric and traffic data of roundabouts corridors, and crash data inventory from national reports related to roundabouts.

- **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 crash prediction models for corridors with roundabouts.**
  This task aims to identify the factor risks at roundabouts corridors for Portuguese conditions and then develop, calibrate and validate crash prediction models. It will be given a particular emphasis on the property damage crashes since they are the most common on those facilities.

- **Task 4: 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 5: 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 6: 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.

A summary of the proposed tasks is depicted in Figure 1.
The expected duration of this research is four years. The major tasks in the first year and second years will be to collect the crash data from the GNR and PSP crash reports related to the roundabouts and traffic systems selected and set up a database of geometric and traffic data of roundabouts corridors (task1). Additionally, the development of numerical emission models for corridors with roundabouts will be made (task2). Further, research will focus on the crash prediction models developed from simulation results and comparison with actual
crash data (task3). In the third year, the modeling simulation platform, the integration of the emission module with the traffic model, as well as the calibration and validation procedures will be developed (task4). After that, traffic scenarios will be implemented and analysed (task5). The modeling platform will be supported by VISSIM model for traffic simulation, and Vehicle Specific Power methodology for emissions estimation. In the last year, a multi-objective analysis (task6) will be made in order to compare the results obtained for different systems of roundabouts. The evolution of activities is described in Table 1.
Table 1: Evolution of the proposed activities.

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4. Summary of the developed work

The following points summarize the preliminary work already undertaken:

- Assessment of the most relevant literature regarding relationship between traffic performance in roundabouts and the impact on fuel use and emissions;
- Development of an experimental design for measurements in roundabouts;
- Real-world measurements of traffic related variables (traffic entry volumes, conflicting volumes, vehicle dynamics, terrain grade) in roundabouts of Aveiro and Coimbra. Data collecting equipment (such as video cameras and GPS units) was installed in vehicles. Video cameras were also installed, to film the interaction between vehicles in roundabouts. The different speed profiles taken by vehicles in the entry and inside the roundabout were characterized using video images. Road experiments were conducted both on non peak and peak periods.

The results of the work already performed can be found at the following papers:


5. Acknowledgments

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