EMPIRICAL ASSESSMENT OF TURBO-ROUNDABOUT OPERATIONS ON TRAFFIC AND EMISSIONS

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ABSTRACT

In the past decade there has been a significant increase in the number of turbo-roundabouts constructed in several European countries. This paper investigates the impact of turbo-roundabouts located in urban areas on pollutant emissions generated from vehicles through an empirical assessment. The research also compares the emissions of vehicles moving through a turbo-roundabout and a conventional multi-lane roundabout. Based on field measurements taken at turbo-roundabouts and multi-lane roundabouts located in Grado (Spain) and Aveiro (Portugal) three representative speed profiles for each speed trajectory type were identified: no stop (I), stop once (II) and multiple stops (III). This study also develops discrete models for turbo-roundabouts and multi-lane roundabouts in which the relative occurrence of those speed profiles is expressed as a function of the entry and the conflicting traffic flows. The Vehicle Specific Power (VSP) methodology is employed to estimate second-by-second pollutant emissions.

This research tests the hypotheses that emissions are impacted by the differences in: 1) the characteristics of speed profiles in each movement; 2) the volumes of entry and conflicting flows; 3) the overall saturation level; and 4) the transportation facility considered (turbo-roundabout /multi-lane roundabout).

The results show that vehicles emit more pollutants at turbo-roundabouts compared with multi-lane roundabouts regardless of the traffic demands at the entry and the circulating areas. These findings suggest that there are no advantages on implementing turbo-roundabouts from an environmental point of view even the capacity of the intersection is rather below to the maximum.

Keywords: Turbo-roundabouts, Multi-lane roundabouts, Speed Profiles, Discrete Models, Traffic performance, Emissions.
1. INTRODUCTION AND OBJECTIVES

Multi-lane roundabouts are associated with higher capacity rates for traffic compared with single-lane roundabouts. Nonetheless, they present some drawbacks such as higher speeds as vehicles negotiate through the roundabout and the possibility of lane changing and weaving maneuvers at the circulating and exit areas, which generate traffic conflicts.

In order to address these problems, the turbo-roundabout concept was developed, as a variation of the conventional multi-lane roundabouts where drivers are required to choose their intended destination before entering the roundabout. The carriageway contains continuous spiral paths in which the entry, the circulating and the exit lanes are usually separated by curbs. Such raised curbs allow eliminating the conflicting points caused by weaving maneuvers and reducing vehicle’s speeds (I).

The first turbo-roundabouts were constructed in the Netherlands, in 2000 (2, 3). Since then, there has been a significant increase in the deployment of turbo-roundabouts in several European countries such as Germany, Finland, Poland, Norway (4), and most recently in Spain (5). There is also a growing awareness about this layout in the United States (6). Their design features are usually based on the Dutch guidelines (2, 3).

A typical concern in the use of turbo-roundabouts is how traffic flows will be impacted. In fact, there are some differences between multi-lane and turbo-roundabouts that affect vehicle operations (I):

i. On a conventional roundabout, the outer circulatory lane at the major entries is used by part of the through movements; on a turbo-roundabout, the opposing traffic is concentrated in a single lane, which leads to a decrease in capacity;

ii. On a conventional roundabout, drivers in the outer lane of the minor entries are affected by all circulating vehicles, even if the trajectories do not actually intersect; on a turbo-roundabout, the outer lane is used only to turn to the right and the opposing traffic is reduced since part of the through traffic is physically separated at the exit;

iii. While right-turning traffic must use the outer entry lane on the conventional roundabout, both inner and outer lanes can be used at the minor entries of a turbo-roundabout.

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

This work seeks to introduce a methodology that can quantify emissions at turbo-roundabouts and explore the effect of turbo-roundabout operations on pollutant emissions and capacity. The methodology described in this study is built on previous research (7, 8) which was dedicated to the environmental impacts of the conventional single-lane and multi-lane roundabouts. It is assumed that emissions and capacity are impacted by the differences in: 1) the characteristics of speed profiles; 2) the volumes of entry and conflicting flows; 3) the overall saturation level; and 4) the considered layout (multi-lane vs. turbo-roundabout).

The research uses an approach founded on experimental measurements of traffic characteristics and saturation levels in turbo-roundabouts to predict the relative occurrence of each speed profile that vehicles experience as they travel in the turbo-roundabout. These speed profiles are: no stopping (I), stop once (II) and multiple stops (III). Emission estimating is then carried out using the Vehicle Specific Power (VSP) methodology (9), which is based on on-board measurements in Light Passenger Vehicles (LPV). Using the developed models, it is possible to estimate the footprints of emissions at any turbo-
roundabout by simply knowing the entry and conflicting flows and identifying the typical speed profile for each trajectory type. Thus, the objectives of this research are threefold:

1) To quantify emissions generated from vehicles at roundabouts ( turbo-roundabout and multi-lane layouts) located in urban areas;
2) To develop appropriate models to explain the interaction between operational variables (entry and conflicting traffic flows) and geometry of a turbo-roundabout;
3) To compare the emissions and capacity impacts of turbo-roundabouts with multi-lane roundabouts.

2. LITERATURE REVIEW

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

From the literature, it is clear that there is not a consensus about the benefits of turbo-roundabouts regarding the available capacity of the intersection. The first studies carried out (10, 11) showed that turbo-roundabouts achieved higher capacity rates than traditional roundabouts with similar design features. Other authors recognized that the relative performance of turbo-roundabouts was toughly influenced by the local traffic conditions (12-14) and layout. Corriere and Guierre explain that depending on each site, the pedestrians, the conflicting traffic flows, the lane capacity, the drivers’ behavior, the balance of the traffic demand on each approach, and the combination of traffic flows at the circulating area will affect each approach capacity and vehicle delay at turbo-roundabouts (15). Vasconcelos et al. proposed a new lane-based capacity methodology to assess the capacity of turbo-roundabout based on gap-acceptance theory. The authors demonstrated that the turbo-roundabout only achieved comparable capacity levels to the traditional two-lane layout when the proportion of right turns at the minor entries was very high. They also confirmed that turbo-roundabout performed worse, in relative terms, as the traffic demand at the main entries increased (16).

Safety benefits of turbo-roundabouts are identified in almost all previous works. Fortuijn (1) identified that the probability of injury crashes was significantly reduced on turbo-roundabouts, and the measured effect of that layout on safety was comparable with that of single-lane roundabouts. Mauro and Cattany (17) concluded that the accident rates can be reduced up to 50% relatively to two-lane roundabouts. Silva et al. (18) pointed out that the benefits of turbo-roundabouts can be attributed to the smallest deflection levels and speed values imposed by the geometric features of that layout.

In spite of having an extensive body of research in macroscopic (e.g. COPERT, MOBILE 6 or TREM), and microscopic emission models (e.g. VT-MICRO, CNEM, VSP, MOVES), their applications on roundabouts case studies are very limited. Average speed models are not recommended in micro scale impact of corridors with traffic interruptions (e.g. pay tools, roundabouts) since they assume that emission rates are constant for all speed ranges. By far the most recognized roundabout traffic model is aaSIDRA (aaTraffic Signalled and unsignalised Intersection Design and Research Aid) which contains vehicle emissions estimates based on a “four-mode” elemental model: deceleration, idle, acceleration, cruise. However, aaSIDRA does not include the impact of stop and go cycles (19).

The Comprehensive Modal Emissions Model (CNEM), Motor Vehicle Emission Simulator (MOVES) and VT-Micro have been previously used in roundabouts research studies (e.g. 20, 21). The findings varied from slight to large reduction/increase in fuel consumption and emissions (20, 21) when using a roundabout over other alternatives.
Instead, an extensive body of research has documented the effective use of the Vehicle Specific Power (VSP) methodology in analyzing the emissions of vehicles at different roundabouts layouts. Coelho et al. (7) identified three characteristic speed profiles for a vehicle approaching single-lane roundabouts: 1) no stop; 2) stop once and 3) multiple stops. They also found that the relative occurrence of these profiles were dependent on the entry and conflicting traffic flows. Based on these findings, the same authors developed regression models for approaching vehicles in single-lane roundabouts. Built on this research, Salamati et al. (8) developed similar regression models in each approaching lane (right vs. left) at multi-lane roundabouts. Lately, Anya et al. (9) employed VSP to explore the environmental benefits posed by a conversion of a signalized intersection to a two-lane roundabout in an urban corridor. They found that the implementation of the roundabout was only relevant at the intersection-level, in the right turn movements from the minor street to the main street. They also concluded 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. (22) 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 interpreted assessment of turbo-roundabouts on several impacts is relatively unknown. Vasconcelos et al. (23) used microsimulation models to evaluate and compare the performance of a single-lane roundabout, in Coimbra, Portugal, and modeled a two-lane roundabout and a turbo-roundabout in terms of capacity, safety and emissions. The analysis results showed that the turbo-roundabout reached higher saturation levels and delays than two-lane roundabout, especially for high proportions of left turns (over than 60%). Concerning emissions, carbon dioxide (CO₂) and nitrogen oxides (NOₓ) were higher in turbo-roundabout, regardless of the proportion of turning movements and/or traffic flows at each approach.

From the literature review, some gaps are inferred. First, the analysis of the turbo-roundabout has been centered on capacity and safety. Second, the researchers did not find any work with the empirical characterization of the relative occurrence of each speed profile in turbo-roundabouts. Third, there is a lack of emissions quantification in turbo-roundabouts, based on real traffic and vehicle dynamics measurements.

The innovation of this study is that it uses empirical data collected on real turbo-roundabouts (traffic flows and vehicle activity data) to estimate emissions. Furthermore, it compares emissions levels of turbo-roundabouts with the conventional multi-lane roundabouts layout.

3. METHODOLOGY
This study is an empirical approach founded on field measurements of the vehicle dynamics as well as the overall congestion level. The methodology overview is depicted in Figure 1. Input data such as entry and conflicting traffic flows (opposite entry traffic), queue length and stop-and-go cycles have been collected using overhead videos of the roundabouts (turbo-roundabouts and multi-lane roundabouts). Vehicle activity data such as second-by-second instantaneous speed, acceleration/deceleration and road topographic conditions (grade) have been collected using a Global Positioning System (GPS) data logger and On-Board Diagnostic (OBD) system. Based on the analysis, the relationship between the congestion level of the roundabouts and the portion of the vehicles that experience each speed profile has been established using discrete models (24). After that, the VSP methodology is used to estimate CO₂, carbon monoxide (CO), NOₓ and hydrocarbons (HC) emissions. Finally, a comparison between the discrete models obtained
from turbo and multi-lane roundabouts is conducted. The aforementioned methodological steps are briefly described herein.

3.1. Characteristic Speed Profiles

Based on vehicle activity, and patterns in speed profiles, there are three different speed profiles that vehicles experience as they approach a generic roundabout (multilane or turbo). It should be mentioned that the relative occurrence of each profile is highly dependent on the level of congestion on the approach (7, 8). The three speed profiles represent:

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

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

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

The main goal of this research is to quantify the relationship between the congestion levels of the roundabouts with the percentage of the vehicles that experience...
each speed profile. These levels of congestion are expressed indirectly as the sum of the entry ($Q_{in}$) and conflicting traffic flows ($Q_{conf}$) at each entry lane (7). The video cameras are used to capture the vehicle movements at the entry and circulating lane of the selected multi-lane and turbo-roundabouts. Both $Q_{in}$ and $Q_{conf}$ are obtained for every 15 minutes of morning and afternoon peak periods. The proportion of the drivers that experience no stopping at the entry ($P_I$), one complete stop ($P_{II}$), multiple stopping ($P_{III}$), the number of stop and go situations and queue lengths are also extracted from the videotapes.

3.2. Discrete Models

By selecting three speed profiles ($P_I$, $P_{II}$ and $P_{III}$), one is intrinsically considering a discrete choice process. Discrete choice models are based on the theory of stochastic utility whereby a choice is made by a decision maker in order to maximize the utility function. This utility function, as shown in Equation (1), is constructed as a combination of known explanatory variables, the systematic part of utility, and a random part which is unknown (24).

$$U_{i,n} = V_{i,n} + \varepsilon_{i,n}$$  \hspace{1cm} (1)

Where:

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

Assuming that the error term of the utility expression is logistically distributed, the multinomial logit model (MNL) is then obtained from Equation (2) (25):

$$P_n(i) = \text{Probability}(U_{i,n} > U_{j,n}) = \frac{e^{V_{i,n}}}{\sum_{j \in C_n} e^{V_{j,n}}}$$  \hspace{1cm} (2)

Where: $C_n$ is the choice set that the decision maker $n$ faces.

For this application, the speed profile of a given vehicle can be expressed as a function of the sum of the entry and conflicting traffic flows ($Q_{total} = Q_{in} + Q_{conf}$), as an indirect measure of the congestion level. Since only differences in utility maker in influencing the choice, the outcome “$P_I$” (no stopping) was chosen as reference. The MNL probabilities for Profiles I, II and III are given by Equations 3, 4 and 5, respectively:

$$P(Y = "P_I") = \frac{1}{1 + e^{\beta_{2,0} + \beta_{2,1}Q_{total}}} + e^{\beta_{5,0} + \beta_{5,1}Q_{total}}$$  \hspace{1cm} (3)

$$P(Y = "P_{II}") = \frac{e^{\beta_{2,0} + \beta_{2,1}Q_{total}}}{1 + e^{\beta_{2,0} + \beta_{2,1}Q_{total}}} + e^{\beta_{5,0} + \beta_{5,1}Q_{total}}$$  \hspace{1cm} (4)

$$P(Y = "P_{III}") = \frac{e^{\beta_{5,0} + \beta_{5,1}Q_{total}}}{1 + e^{\beta_{2,0} + \beta_{2,1}Q_{total}}} + e^{\beta_{5,0} + \beta_{5,1}Q_{total}}$$  \hspace{1cm} (5)

Where the different $\beta_{i,j}$ are the model parameters to be estimated from the sample data:
\[ \beta_{2,0} \text{ and } \beta_{2,1} = \text{intercept and coefficient for outcome “Profile II”} \]
\[ \beta_{3,0} \text{ and } \beta_{3,1} = \text{intercept and coefficient for outcome “Profile III”} \]

3.3. Site Selection

Two sets of roundabouts were selected for this study – three multi-lane roundabouts and three turbo-roundabouts. Figure 2 displays the aerial view of the data collection sites investigated in this study as well as the studied approaches. Three turbo-roundabouts along the N-634 national road in the city of Grado, Spain were selected, as exhibited in Figure 2 (a-c). These turbo-roundabouts were selected because in Portugal such layout was not yet constructed in current intersections. Thus, it was intended to represent Iberian case studies. These turbo-roundabouts were constructed and opened in 2009 (5). The through movement from the northeast-bound approach was studied by the use of GPS and OBD runs in different directions. That approach has two entry lanes from 200 meters to the yield lane of turbo-roundabout. The right lane only provides movements to the first exit while the left lane allows turning movements to the remaining exits. Concerning multi-lane roundabouts, as exhibited in Figure 2 (d-f), they are placed in the urban area of Aveiro, Portugal, and have two entry lanes on their approaches and two circulating lanes.

The posted speed limit in the studied areas is 40 km/h. Sites characteristics such as location, circulating width, and the entry, the circulating and the exit speeds are summarized in Table 1. The morning entry traffic flow is also provided.

It should be mentioned that these turbo-roundabouts, at the moment of field tests, do not have a curb raised divider (only longitudinal marking-double lines). However, almost every vehicle correctly uses the inner and outer lanes to their intended destination.
**FIGURE 2** Aerial View of the three data collection Turbo-roundabouts, Grado, Spain: a) TR1; b) TR2; c) TR3 and Multi-lane roundabouts, Aveiro, Portugal: d) ML1; e) ML2; f) ML3.

**TABLE 1** Key characteristics of the selected roundabouts

<table>
<thead>
<tr>
<th>ID</th>
<th>Entry Speed (km/h)</th>
<th>Exit Speed (km/h)</th>
<th>Circulating Speed (km/h)</th>
<th>Circulating Width (m)</th>
<th>Entry Traffic (vph)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TR1</td>
<td>18.8</td>
<td>21.5</td>
<td>15.8</td>
<td>6.0</td>
<td>275</td>
</tr>
<tr>
<td>TR2</td>
<td>21.8</td>
<td>21.7</td>
<td>17.0</td>
<td>6.2</td>
<td>500</td>
</tr>
<tr>
<td>TR3</td>
<td>27.5</td>
<td>25.7</td>
<td>26.5</td>
<td>6.1</td>
<td>435</td>
</tr>
<tr>
<td>ML1</td>
<td>34.1</td>
<td>40.2</td>
<td>30.1</td>
<td>8.3</td>
<td>585</td>
</tr>
<tr>
<td>ML2</td>
<td>32.2</td>
<td>34.2</td>
<td>24.1</td>
<td>8.2</td>
<td>660</td>
</tr>
<tr>
<td>ML3</td>
<td>24.0</td>
<td>35.0</td>
<td>26.1</td>
<td>8.1</td>
<td>470</td>
</tr>
</tbody>
</table>

*Average values of traffic flows (right and left lanes) observed at the morning peak period (8-9 a.m.).
3.4. Data Collection and Emission Estimation

This work applied field data collection methodologies to get traffic characteristics of the two roundabouts layouts. The research team scouted and collected data at the roundabouts during morning (8:00 – 11:00 a.m.) and afternoon (5:00 – 8:00 p.m.) peak periods in typical weekdays (Tuesday to Wednesday). The following data was collected:

- Entry and conflicting traffic flows;
- Queue Length;
- Number of stop-and-go cycles;
- Vehicle activity data (speed, acceleration/deceleration and grade).

Entry and conflicting traffic flows, queue lengths and the number of stop-and-go were gathered from overhead videos installed at strategic points of the roundabouts, as illustrated in Figure 2. The vehicle activity data characterization was recorded using a Renault Clio Sport Tourer Euro V Emission Standard (LPV) making several turning movements at the roundabouts. The QSTARZ GPS Travel Recorder (26) was used to acquire some of the parameters related to the vehicle activity data (second-by-second speed and acceleration/deceleration) and the selected sites characteristics (road grade, latitude and longitude). Along with the GPS, an 8226B CarChip Pro by Davis Instruments was used. The CarChip Pro is an OBD that records second-by-second vehicle dynamics, such as vehicle speed, distance traveled, and acceleration and deceleration rates (27). For each data collection trip, the vehicle was equipped with the OBD and a GPS. Later, the data from OBD and GPS were coordinated to check the vehicle dynamics (speed, acceleration /deceleration rates) needed for analysis.

A total of 240 GPS travel runs of through movement (approximately 40 at each location) were extracted and identified for this research (approximately 400 km of road coverage over the course of 15 hours). To reduce systematic errors, 3 different drivers (all male, ages 25 to 35 with varying levels of driving experience) performed an identical number of trips (approximately 40 each one) on each roundabout movement. Concurrently, over 21 hours of video data were gathered from the six roundabouts approaches (approximately 3.5 hours at each location).

One widely used approach based on regression based models is the pollutant emissions estimation, through the concept of VSP. This is a methodology introduced by Jimenez-Palacios (28), which provides the characterization of the vehicle activity data on a second-by-second basis. VSP values are categorized in 14 modes of engine regime, and an emission factor for each mode is used to estimate CO\textsubscript{2}, CO, NO\textsubscript{X} and HC emissions for Light Passenger Vehicles (LPV) (29). Kolak et al. (30) and Coelho et al. (31) recognized that a VSP based emission model leads to a better estimation of vehicle emissions (30) and regional air quality concentrations (31) than an average speed-based emissions model. For a typical LPV VSP is estimated as (32):

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

Where:

- \(VSP\) = Vehicle Specific Power (kW/ton);
- \(v\) = Instantaneous speed (m/s);
- \(a\) = Instantaneous acceleration or deceleration (m/s\(^2\));
- \(grade\) = Terrain gradient (decimal fraction).
The average emission rates for pollutants CO₂, CO, NOₓ and HC for each VSP mode for LPGV with engine size <1.4l, Light Passenger Diesel Vehicles (LPDV) <1.9l and Light Commercial Diesel Vehicles (LCDV) <2.5l are presented in Table 2. The authors tried to fit as much as possible the characteristics of the emissions to the characteristics of local fleet compositions, namely the engine capacity, average age of vehicles and fuel type. Accordingly, such emission rates can be applied for a European car fleet (e.g. 23-33) since they include a wide range of engine displacement values.

### TABLE 2 Mean Values for CO₂, CO, NOₓ and HC emission rates (g/s) for VSP modes for LDGV, LDDV and LCDV

<table>
<thead>
<tr>
<th>Vehicle Type</th>
<th>Definition (kW/ton)</th>
<th>VSP Mode</th>
<th>Average modal emission rates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light Duty Gasoline Vehicles (LDGV)</td>
<td>VSP ≤ -2</td>
<td>1</td>
<td>CO₂ (g/s), CO (g/s), NOₓ (g/s), HC (g/s)</td>
</tr>
<tr>
<td></td>
<td>VSP -2 ≤ VSP &lt; 0</td>
<td>2</td>
<td>1.67, 0.008, 0.0009, 0.0004</td>
</tr>
<tr>
<td></td>
<td>VSP 0 ≤ VSP &lt; 4</td>
<td>3</td>
<td>1.14, 0.003, 0.0003, 0.0004</td>
</tr>
<tr>
<td></td>
<td>VSP 1 ≤ VSP &lt; 4</td>
<td>4</td>
<td>2.23, 0.008, 0.0012, 0.0004</td>
</tr>
<tr>
<td></td>
<td>VSP 4 ≤ VSP &lt; 7</td>
<td>5</td>
<td>2.92, 0.011, 0.0017, 0.0005</td>
</tr>
<tr>
<td></td>
<td>VSP 7 ≤ VSP &lt; 10</td>
<td>6</td>
<td>3.53, 0.017, 0.0024, 0.0007</td>
</tr>
<tr>
<td></td>
<td>VSP 10 ≤ VSP &lt; 13</td>
<td>7</td>
<td>4.11, 0.020, 0.0031, 0.0008</td>
</tr>
<tr>
<td></td>
<td>VSP 13 ≤ VSP &lt; 16</td>
<td>8</td>
<td>4.64, 0.029, 0.0042, 0.0010</td>
</tr>
<tr>
<td></td>
<td>VSP 16 ≤ VSP &lt; 19</td>
<td>9</td>
<td>5.16, 0.036, 0.0051, 0.0011</td>
</tr>
<tr>
<td></td>
<td>VSP 19 ≤ VSP &lt; 23</td>
<td>10</td>
<td>5.63, 0.055, 0.0059, 0.0014</td>
</tr>
<tr>
<td></td>
<td>VSP 23 ≤ VSP &lt; 28</td>
<td>11</td>
<td>6.53, 0.114, 0.0076, 0.0021</td>
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<tr>
<td></td>
<td>VSP 28 ≤ VSP &lt; 33</td>
<td>12</td>
<td>7.59, 0.208, 0.0121, 0.0034</td>
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<tr>
<td></td>
<td>VSP 33 ≤ VSP &lt; 39</td>
<td>13</td>
<td>9.02, 0.442, 0.0155, 0.0049</td>
</tr>
<tr>
<td></td>
<td>VSP ≥ 39</td>
<td>14</td>
<td>10.09, 0.882, 0.0179, 0.0109</td>
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<tr>
<td>Light Duty Diesel Vehicles (LDDV) (34)</td>
<td>VSP ≤ -2</td>
<td>1</td>
<td>0.21, 0.00003, 0.0013, 0.00014</td>
</tr>
<tr>
<td></td>
<td>VSP -2 ≤ VSP &lt; 0</td>
<td>2</td>
<td>0.61, 0.00007, 0.0026, 0.0011</td>
</tr>
<tr>
<td></td>
<td>VSP 0 ≤ VSP &lt; 4</td>
<td>3</td>
<td>0.73, 0.00014, 0.0034, 0.0011</td>
</tr>
<tr>
<td></td>
<td>VSP 1 ≤ VSP &lt; 4</td>
<td>4</td>
<td>1.50, 0.00025, 0.0061, 0.0017</td>
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<tr>
<td></td>
<td>VSP 4 ≤ VSP &lt; 7</td>
<td>5</td>
<td>2.34, 0.00029, 0.0094, 0.0020</td>
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<td>6</td>
<td>3.29, 0.00069, 0.0125, 0.0023</td>
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<td></td>
<td>VSP 10 ≤ VSP &lt; 13</td>
<td>7</td>
<td>4.20, 0.00058, 0.0155, 0.0024</td>
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<td>4.94, 0.00064, 0.0178, 0.0023</td>
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<td></td>
<td>VSP 16 ≤ VSP &lt; 19</td>
<td>9</td>
<td>5.57, 0.00061, 0.0213, 0.0024</td>
</tr>
<tr>
<td></td>
<td>VSP 19 ≤ VSP &lt; 23</td>
<td>10</td>
<td>6.26, 0.00101, 0.0325, 0.0028</td>
</tr>
<tr>
<td></td>
<td>VSP 23 ≤ VSP &lt; 28</td>
<td>11</td>
<td>7.40, 0.00115, 0.0558, 0.0037</td>
</tr>
<tr>
<td></td>
<td>VSP 28 ≤ VSP &lt; 33</td>
<td>12</td>
<td>8.39, 0.00096, 0.0743, 0.0042</td>
</tr>
<tr>
<td></td>
<td>VSP 33 ≤ VSP &lt; 39</td>
<td>13</td>
<td>9.41, 0.00077, 0.1042, 0.0040</td>
</tr>
<tr>
<td></td>
<td>VSP ≥ 39</td>
<td>14</td>
<td>10.48, 0.00073, 0.1459, 0.0042</td>
</tr>
<tr>
<td>Light Commercial Diesel Vehicles (34)</td>
<td>VSP ≤ -2</td>
<td>1</td>
<td>0.29, 0.00003, 0.0015, 0.0003</td>
</tr>
<tr>
<td></td>
<td>VSP -2 ≤ VSP &lt; 0</td>
<td>2</td>
<td>0.84, 0.00004, 0.0039, 0.0005</td>
</tr>
<tr>
<td></td>
<td>VSP 0 ≤ VSP &lt; 1</td>
<td>3</td>
<td>1.07, 0.00004, 0.0066, 0.0004</td>
</tr>
<tr>
<td></td>
<td>VSP 1 ≤ VSP &lt; 4</td>
<td>4</td>
<td>2.55, 0.00008, 0.0094, 0.0009</td>
</tr>
<tr>
<td></td>
<td>VSP 4 ≤ VSP &lt; 7</td>
<td>5</td>
<td>4.34, 0.00016, 0.0160, 0.0013</td>
</tr>
<tr>
<td></td>
<td>VSP 7 ≤ VSP &lt; 10</td>
<td>6</td>
<td>6.14, 0.00027, 0.0254, 0.0015</td>
</tr>
<tr>
<td></td>
<td>VSP 10 ≤ VSP &lt; 13</td>
<td>7</td>
<td>8.20, 0.00044, 0.0356, 0.0025</td>
</tr>
<tr>
<td></td>
<td>VSP 13 ≤ VSP &lt; 16</td>
<td>8</td>
<td>9.90, 0.00054, 0.0433, 0.0044</td>
</tr>
<tr>
<td></td>
<td>VSP 16 ≤ VSP &lt; 19</td>
<td>9</td>
<td>11.27, 0.00060, 0.0518, 0.0097</td>
</tr>
<tr>
<td></td>
<td>VSP 19 ≤ VSP &lt; 23</td>
<td>10</td>
<td>12.34, 0.00063, 0.0518, 0.0097</td>
</tr>
<tr>
<td></td>
<td>VSP 23 ≤ VSP &lt; 28</td>
<td>11</td>
<td>13.28, 0.00071, 0.0645, 0.0082</td>
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<tr>
<td></td>
<td>VSP 28 ≤ VSP &lt; 33</td>
<td>12</td>
<td>15.77, 0.00080, 0.0736, 0.0073</td>
</tr>
<tr>
<td></td>
<td>VSP 33 ≤ VSP &lt; 39</td>
<td>13</td>
<td>17.55, 0.00091, 0.0838, 0.0083</td>
</tr>
<tr>
<td></td>
<td>VSP ≥ 39</td>
<td>14</td>
<td>19.38, 0.00103, 0.0945, 0.0093</td>
</tr>
</tbody>
</table>

1 As computed by Equation 6
After that, the pollutant emissions per vehicle due to the three speed profiles are aggregated in order to evaluate the overall impact of a change in the average trajectory through the roundabout. Equation 7 provides the estimation of hourly emissions generated by vehicles entering a roundabout by using VSP methodology:

$$E_{TR} = Q_m \left( E_i \times P_i + E_{II} \times P_{II} + E_{III} \times P_{III} \right)$$  \hspace{1cm} (7)

Where:

- $E_{TR}$ = Hourly emissions at the turbo-roundabout (g);
- $E_i$ = Emission per vehicle associated with each speed profile $i = I, II$ and $III$ (g);
- $P_i$ = Proportion of vehicles that experienced each speed profile $i = I, II$ and $III$;
- $Q_m$ = Entry flow rate (vph).

The pollutant emission values of CO$_2$, CO, NO$_X$ and HC are estimated from the distribution of VSP time spent in modes obtained from the GPS runs. Therefore $E_i$ is given by the Equation 8:

$$E_{ij} = \sum_{m=1}^{N_m} F_{mj}$$  \hspace{1cm} (8)

Where:

- $E_{ij}$ = Total emissions for source pollutant (g);
- $m$ = Label for second of travel (s);
- $i$ = Speed profile (I, II and III)
- $j$ = Source pollutant;
- $F_{mj}$ = Emission factor for pollutant $j$ in label for second of travel $m$ (g/s);
- $N_m$ = Number of seconds (s).

To estimate the pollutant emissions for each speed profile ($E_i$), second-by-second emission rates for the vehicles which experience that speed profile is obtained from Equation 6. It should be noted that a fixed travel distance across the roundabout must be used to calculate a complete $E_i$ second-by-second dynamics for a given speed profile. Thus, a roundabout influence area was defined as the sum of the deceleration distance that a vehicle decelerated from cruise speed as it approaches the roundabout, enters the circulating lane and acceleration distance as it leaves the roundabout up to the point that attains the cruise speed. For this analysis, an average roundabout influence area of 250 m was considered. Since the case studies are located on relatively flat grades the effect of that parameter was negligible. For both roundabouts layouts the following distribution fleet composition was used (35): 45% of LPGV, 34% of LPDV and 21% of LCDV.

4. RESULTS AND DISCUSSION

This section presents and discusses the main results from discrete models for turbo-roundabouts and multi-lane roundabouts, and characteristic speed trajectories from turbo and multi-lane roundabouts. Further, pollutant emission impacts (CO$_2$, CO, NO$_X$ and HC) of the two layouts are compared.

4.1. Predictive Discrete Models

Two MNL models were obtained – one for multilane roundabouts, other for turbo-roundabouts. The models were calibrated through maximum likelihood using the SPSS
software (see Table 3). The sample is comprised of 3162 observations in three two-lane roundabouts and 2498 observations in three turbo-roundabouts. Each of these cases was recorded in a database with three fields: roundabout type (Multi-lane – ML or Turbo-roundabouts – TR), speed profile ($P_1$, $P_2$ or $P_3$) and total traffic flow (15 minutes period).

### TABLE 3 Calibrated coefficients for the MNL model

<table>
<thead>
<tr>
<th>Speed profile</th>
<th>$x$</th>
<th>$B$</th>
<th>Std. Error</th>
<th>Wald</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_1$</td>
<td>$\beta_{2,0}$</td>
<td>$-2.85$</td>
<td>$0.17$</td>
<td>276.3</td>
<td>.00</td>
</tr>
<tr>
<td>$Q_{total}$</td>
<td>$\beta_{3,1}$</td>
<td>$0.00$</td>
<td>$86.3$</td>
<td>.00</td>
<td></td>
</tr>
<tr>
<td>$P_2$</td>
<td>$\beta_{3,0}$</td>
<td>$-7.55$</td>
<td>$0.62$</td>
<td>146.4</td>
<td>.00</td>
</tr>
<tr>
<td>$Q_{total}$</td>
<td>$\beta_{3,1}$</td>
<td>$0.008$</td>
<td>$62.0$</td>
<td>.00</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Speed profile</th>
<th>$x$</th>
<th>$B$</th>
<th>Std. Error</th>
<th>Wald</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_1$</td>
<td>$\beta_{2,0}$</td>
<td>$-2.984$</td>
<td>$0.16$</td>
<td>340.7</td>
<td>.00</td>
</tr>
<tr>
<td>$Q_{total}$</td>
<td>$\beta_{3,1}$</td>
<td>$0.002$</td>
<td>$208.6$</td>
<td>.00</td>
<td></td>
</tr>
<tr>
<td>$P_2$</td>
<td>$\beta_{3,0}$</td>
<td>$-8.619$</td>
<td>$0.45$</td>
<td>366.5</td>
<td>.00</td>
</tr>
<tr>
<td>$Q_{total}$</td>
<td>$\beta_{3,1}$</td>
<td>$0.006$</td>
<td>$295.3$</td>
<td>.00</td>
<td></td>
</tr>
</tbody>
</table>

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

Figure 3 illustrates the two calibrated MNL models. As expected, the probability of a driver being able to negotiate the roundabout without stopping ($P_1$) decreases as the total traffic flow increases. Moreover, the comparison of the two graphs shows that the probability for one or more stops ($P_2$ and $P_3$), for the same total traffic, is higher in the turbo-roundabouts. This happens essentially because on the two-lane roundabouts the conflicting traffic is divided by two lanes, which increases the number of large gaps available for the vehicles waiting at the yield line (16).

![a) Multi-lane roundabouts](image1)

![b) Turbo-roundabouts](image2)

**FIGURE 3 Predictive models for the relative occurrence of speed profiles I, II and III: a) multilane roundabouts; b) turbo roundabouts.**

### 4.2. Vehicles trajectories at turbo-roundabouts and multi-lane roundabouts

As mentioned before, the relative occurrence of the speed profiles are found to be dependent on the prevailing levels of the traffic demand levels at the roundabout ($Q_{total} = Q_{in} + Q_{conf}$). From the observation of the overhead cameras taken at the turbo-roundabouts, it was noted that due to low circulating speed values (see Table 1 for those details), the idle times and stop-and-go situations along the approach lane were significant. Thus, the vehicle’s dynamics through the two layouts is quite different. With this concern in mind, two sets of speed profiles (I, II and III) for the turbo and multi-lane roundabouts were selected to assess the differences in emissions. These speed profiles are the representative
average speed trajectories for turbo-roundabout and a multi-lane roundabout using multiple field data GPS runs collected through the studied cases. To maintain consistency between layouts, similar travel distance, posted speed and traffic flows (entry and conflicting flows) values were used.

Figure 4 displays the speed profiles for through movements of the turbo-roundabout TR2 and multi-lane roundabout ML2 (from the left entry lane) for each speed profile and the correspondent percent time in each VSP mode (considering all performed runs and all drivers). These speed trajectories are later used to estimate emissions from the turbo-roundabout and multi-lane roundabout using the predictive regression models developed for each case.

Based on the raw distributions of VSP modes from the turbo-roundabout for speed profile I, vehicles spent most of the time in VSP modes 1, 2, 3 and 4 which corresponds to decelerations as vehicles approach the turbo-roundabout (modes 1 and 2), enter the circulating lanes at low speeds or stop (mode 3) and accelerations as they exit the turbo-roundabout (mode 4). The percent of the time spent in VSP modes higher than 4 and 5 for the turbo-roundabout is on average lower across the three speed profiles compared to multi-lane roundabout on speed profile I. This means that vehicles at the turbo-roundabout experienced moderate speeds (perhaps due to higher deflection angles and low circulating speeds). However, a vehicle travelling in turbo-roundabout faces with higher idle and low speed situations at the downstream and circulating areas compared to a vehicle traveling in multi-lane roundabout, especially in speed profiles II and III. The percent of the time spent in mode 3 confirm these findings.
FIGURE 4 Average speed trajectory over distance and total seconds spent in each VSP model (and 95% estimated confidence intervals) for each speed profile: a) I, b) II, c) III.

4.3. Emission rates

This section employs the predictive discrete models and trajectories of each speed profile I, II and III to calculate and compares the emissions produced by vehicles at turbo-roundabout and multi-lane roundabout. According to the different values of the entry and conflicting flows, the percentage of the vehicles that experience any of the three speed profiles at turbo-roundabouts are identified from Figure 3. After that, the total emissions for each speed trajectory in each layout are calculated from Equations 6, 7 and 8, using second-by-second speed trajectory exhibit in Figure 4, and considering the composition fleet distribution presented in the section 3.4.

Following the previous results, six scenarios of traffic demand are established with the main goal of compare the CO₂, CO, NOₓ and HC emissions for turbo-roundabout and
multi-lane roundabout. The pollutant emission effects of both layouts were explored at two levels: 1) sum of the entry and conflicting flows; and 2) total saturation level. The following scenarios are:

- Scenario 1: $Q_{in} = Q_{conf} = 100 \text{ vph} (Q_{total} = 200 \text{ vph})$;
- Scenario 2: $Q_{in} = Q_{conf} = 200 \text{ vph} (Q_{total} = 400 \text{ vph})$;
- Scenario 3: $Q_{in} = Q_{conf} = 300 \text{ vph} (Q_{total} = 600 \text{ vph})$;
- Scenario 4: $Q_{in} = Q_{conf} = 400 \text{ vph} (Q_{total} = 800 \text{ vph})$;
- Scenario 5: $Q_{in} = Q_{conf} = 500 \text{ vph} (Q_{total} = 1000 \text{ vph})$;
- Scenario 6: $Q_{in} = Q_{conf} = 600 \text{ vph} (Q_{total} = 1200 \text{ vph})$.

These scenarios were based on the video observations of traffic flows on both roundabouts layouts and the hypothesis of this study. The hypothesis are:

- Different flow rates affect the emissions for multi-lane roundabouts and turbo-roundabouts;
- Vehicles in the turbo-roundabout face higher stop-and-go situations compared with vehicles in multiline roundabouts and this observation might affect the emissions;
- Highly-congested and low-congested traffic periods may have different effects on the emissions on both roundabouts layouts.

The comparison of hourly emissions (g) for the turbo-roundabout and multi-lane for CO$_2$, CO, NO$_X$ and HC are illustrated in Figure 5. The results show that both in low and moderate congestion levels (scenarios 1-4) the pollutant emissions generated from vehicles at the turbo-roundabout are higher than those verified at the multi-lane roundabout (15%, 20%, 15% and 19% for CO$_2$, CO, NO$_X$ and HC, respectively). For high flow rates (scenarios 5-6), turbo-roundabout yields even more emissions than multi-lane roundabout (21%, 24%, 17% and 28% for CO$_2$, CO, NO$_X$ and HC, respectively). This is possible due to the longer stop-and-go cycles that vehicles experience at the turbo-roundabout since they have mostly speed profiles II (>33%) or III (>36%) in high flow rate scenarios.

It should be emphasized that vehicles circulate at low speed at the circulating areas of the turbo-roundabouts when compared with multi-lane layout, as illustrated in Figure 4. Accordingly, they spend high travel time in the turbo-roundabout (assuming equal travel distance). This explains the similar trends yield in CO$_2$, CO, NO$_X$ and HC graphs. Overall, the main conclusion from Figure 5 is that the time spent by vehicles, as a result of the difference between cruise and circulating speeds, has more impact on emissions in turbo-roundabout than the deceleration/acceleration rates.

Note that the relative difference between emissions produce at the turbo and multi-lane roundabouts is not sensitive to any other conditions such as conflicting flow or congestion level. These findings are in line with previous research taken at turbo-roundabouts in which those layouts produced an amount of CO$_2$ and NO$_X$ emissions higher than multi-lane roundabouts (19).
a) FIGURE 5 Variation of total emission (g) per hour for different traffic scenarios (and 95% estimated confidence intervals): a) CO$_2$; b) CO; c) NO$_X$ and d) HC.

5. CONCLUSIONS

This paper explored the impact of turbo-roundabouts on pollutant emissions, using a methodology based on real measurements of traffic performance of vehicles. This study also compared the emissions for vehicles travelling in a turbo-roundabout and multi-lane roundabouts. In order to estimate overall emissions, the methodology had the following steps:

1. To develop discrete models to establish a relationship between distinct speed profiles (no stop, stop once and several stops) that vehicles experience at roundabouts (turbo and multi-lane roundabouts) and traffic conditions (entry and conflicting flows);
2. To select a representative speed profile for each trajectory type (assuming that each roundabout layout had similar entry speeds);
3. To calculate the VSP distribution for each representative trajectory type (identified from Step 2);
4. To calculate the hourly pollutant emissions from discrete models that estimate the proportion of entry volume for each speed profiles occurrence (step 1), and multiply them by the correspondent VSP for each trajectory type.

The findings of this paper showed that vehicles circulating in turbo-roundabouts, considering a through movement, produced more emissions (16-22%, depending on the pollutant) when compared with conventional multi-lane roundabouts. Thus, there is no advantage on the implementation of turbo-roundabouts from an environmental point of
view even the capacity of the intersection is rather below to the maximum. Nevertheless, there is some future work that can be developed:

- More data gathering in turbo-roundabouts, namely 1) with different configurations (these three turbo-roundabouts have small inscribed circles and circulating widths); 2) with higher traffic volumes; 3) with higher variability in terms of speeds, approach geometries and traffic flows among turbo-roundabouts; and 4) with the presence of a curb raised divider that may affect vehicles’ maneuver along the turbo-roundabout (in the measured turbo-roundabouts there were longitudinal marking-double lines only);

- Improvement of the developed predictive discrete models for speed profiles should be improved by linking the speed profile to the entry capacity and saturation rate. These performance measures can be effectively estimated using well-established models based on the gap-acceptance theory. The resulting predictive models can then be applied to different geometries or directional splits of the approach traffic;

- Use of a Portable Emissions Measurement System (PEMS) to collect field emissions on those sites (or other with equivalent fleet composition) would be useful and meaningful. This procedure would provide a validation of emission results and enhance the accuracy of the developed models.

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REFERENCES


3. CROW. Turborotondes, publication 257. Ede, April, 2008.


23. Vasconcelos, L., A. B. Silva, A. B. Seco, P. Fernandes, and M. C. Coelho. Turbo Roundabouts: Multicriterion Assessment on Intersection Capacity, Safety, and


28. Palacios, J. *Understanding and quantifying motor vehicle emissions with vehicle specific power and TILDAS remote sensing*. Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, MA, 1999.


