Emission Estimation at Multilane Roundabouts: Effect of Movement and Approach Lane

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ABSTRACT
This research explores the effect of multilane roundabouts located on urban corridors on traffic performance and pollutant emissions generated from vehicles. It further compares the emission of vehicles moving through the roundabout as they use either the entry left or right lanes.

The methodology described in this paper can be generalized to measure the emissions of any multilane roundabout. The paper identified a representative speed profile for each speed trajectory type, no stop (I), one stop (II) and multiple stops (III), from field data collection at four multilane roundabouts in Aveiro, Portugal. Then, the "Vehicle Specific Power" (VSP) emission methodology is employed to estimate the second-by-second emissions generated from a vehicle during different acceleration-deceleration cycles. This paper also develops predictive regression models using congestion-specific vehicle speed profiles for two-lane roundabout approaches to predict the percentage of vehicles that experience different speed trajectory types in the roundabout. The paper further employs the predictive models and second-by-second speed profiles into VSP methodology to compare the emission generated from a vehicle entering the roundabout using right lane with a vehicle entering the roundabout using left lane.

This paper tests the hypotheses that differences in; a) the characteristics of speed profiles in each lane (left v.s. right lane); b) conflicting flows for left and right lane; c) lane flow; and d) overall congestion level effects the emission amounts generated from vehicles in each lane. The analysis shows that under low congestion levels vehicles in right lane emit more pollutant because they have on average higher speeds and sharper acceleration and deceleration rates. For high congestion levels if flow rates for left and right lanes are equal, vehicles in left lane produce more emission since vehicles in left lane experience longer stop-and-go cycles and have different speed profile than vehicles in right lane.

INTRODUCTION AND OBJECTIVES
Roundabouts are proven to be a safety countermeasure for intersections by Federal Highway Administration (FHWA) (1). Roundabouts reduce the unnecessary number of stops for vehicles compared to stop-controlled intersections. According to the delay formula for roundabouts in Highway Capacity Manual (HCM 2010), delay at roundabouts is either lower or the same value as all-way stop-controlled intersections (2). Compared to stop-controlled intersections, roundabouts also improve the capacity of intersection (3). 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 (3). 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.

This paper intends to explore the effect of multi-lane roundabout operation on pollutant emissions segregated by lane utilization (left or right). The research methodology in this paper builds on previous research by Coelho et al. (4) which focused on single lane roundabouts. The methodology and the models presented in this research can be generalized and employed to measure emissions of multilane roundabouts in general. The limitations of this research are also explained in the conclusions and limitations section at the end.
The motivation for this paper is first to introduce a general methodology and framework to measure the emissions of multilane roundabouts. It is hypothesized that roundabout emissions for left lane and right lane approaches might vary due to differences in speed and traffic characteristics of the lanes. This paper tests the hypotheses that differences in: a) the characteristics of speed profiles in each lane (left v.s. right lane); b) conflicting flows for left and right lane; c) lane flow; and d) overall congestion level effects the emission amounts generated from vehicles in each lane.

This paper uses experimental measurements of traffic characteristics and congestion levels in roundabouts to predict the frequency of the three speed trajectory types, no stop (I), one-stop (II), and multiple stops (III), at two-lane approaches of multi-lane roundabouts. By employing field data collection of speed trajectories of vehicles at the roundabout and utilizing the “Vehicle Specific Power” (VSP) approach (5) the authors were able to measure an overall pollution estimate for multilane roundabouts.

The researchers will be able to implement the methodology and models developed in this paper to measure any multilane roundabout emissions by knowing the traffic flow (entry and circulating) of the roundabout and identifying a representative second-by-second speed profile for each trajectory type for the roundabout.

**LITERATURE REVIEW**

Research studies have used various methodologies to describe the environmental effect of roundabout operations. Many of the studies have used simulation models to integrate simulation-generated vehicle dynamics data to microscopic emission models and quantify the effect of roundabouts on pollutant emissions. Mandavilli et al. (6) used aaSIDRA to compare the emissions produced from stop controlled intersections with single-lane roundabouts. Hallmark et al. (7) found that signalized intersections yield higher emission rates (CO, NOx) than alternative roundabouts by simulating in aaSIDRA and MOBILE6.2 (8). Ahn et al. (9) chose to create microscopic simulation models in INTEGRATION and VISSIM to compare emissions produced in a signalized and stop controlled intersection and a roundabout. Their study showed stop-controlled intersections have lower emission rates than other two alternatives.

Applications of simulation models to compare emission rates of different facilities bring some complexities to the analysis. The vehicle dynamics construction from simulation modeling (speed profiles, acceleration and deceleration rates and distances) are required to be calibrated and validated based on field data. Emission analysis of a macroscopic simulation model such as aaSIDRA is based on four main factors: cruise speed, acceleration rate, deceleration rate and idle time (10). The models usually result in sharp acceleration or deceleration rates, therefore; they don’t take into account the fluctuations of vehicle speed in different stop and go cycles as the vehicle navigates through the roundabout (11). Swidan et al. (12) compared the vehicle dynamics and emission generated from a field data collection of a road network with simulated model of the same network in AIMSUN. Their study showed that the two methodologies result in minor differences due to variations of vehicle dynamics in AIMSUN and field data. Nevertheless, the difference was much more significant on arterial streets.

Other research studies consider the use of vehicle dynamics from field data collection. Coelho et al. (4) were able to quantify traffic and emission impacts of single-lane roundabout operations on urban corridors. Their research is based on empirical data collected at single-lane roundabouts in U.S. and Portugal. They identify the characteristics of vehicle dynamics associated with different speed profiles for a vehicle approaching a single-lane roundabout. By using the empirical speed profiles Coelho et al. (4) found that at single-lane roundabouts the increase in emission has a direct relationship with the increase in
conflicting traffic with existence of queue at the entry. Emission rate for CO, NOx and HC have an
crude increase even with low values of conflicting traffic due to high acceleration rates at entry with low
conflicting flow. They also predicted that emission rates increase as the difference between cruise speed
and circulating speed increases (4).

The majority of current literature on roundabout emissions has focused on single-lane roundabouts or
using simulation modeling to estimate the emissions of roundabouts in general. The novelty of this
research is that it uses field data collection of roundabout traffic volumes, vehicle dynamics such as
instantaneous speed, acceleration and roundabout geometry to measure the emission of multilane
roundabouts as well as investigates the roundabout emission by segregating each entry movement lane
(left and right).

METHODOLOGY

The authors collected experimental data on vehicle dynamics for through movements from left lane and
right lanes from four roundabouts in Aveiro, Portugal, in order to investigate and compare the amount of
emissions produced from vehicles located in either lane. Figure 1 shows the overview of the
methodology. Input data such as entry and circulating traffic flow and queue length have been collected
using overhead videos of the roundabouts. Microscopic vehicle dynamics such as second-by-second
instantaneous speed, acceleration or braking and grade have been collected using GPS devices and On-
Board Diagnostic (OBD) system. Based on the analysis the speed profiles for each trajectory types have
been identified. Finally the VSP methodology was applied to calculate pollutant emissions (13). The
traffic model analysis and emission calculations are explained in detail in the following sections.
Vehicles at the roundabout entry approach may have three different characteristic speed profiles. In speed profile (I), a vehicle decelerates while approaching the roundabout, enters the circulating traffic without a complete stop and accelerates while exiting the roundabout; in speed profile (II), a vehicle decelerates while approaching the roundabout, comes to a complete stop at the yield line to negotiate conflicting traffic and finds a crossable gap, then accelerates to enter the circulating lane and exits the roundabout; in speed profile (III), a vehicle decelerates to join a queue at the entrance of a roundabout, experiences multiple stop-and-go cycles to reach the yield line, then accelerates to enter the circulating lane and exits the roundabout. A more detailed description of each speed profile can be found in the research by Coelho et al. (4).
The first goal of this paper is to quantify the relationship between the congestion level of the roundabout (entry flow and circulating flow) with the portion of the vehicles that experience each speed profile. The data needed for this section of the analysis is the values for conflicting flow and entry flow for every 15 minutes to estimate the portion of the vehicles that experience the three speed profiles (I, II, III). The proposed data collection methodology uses video cameras to capture the vehicle movements at the entry and circulating lane of candidate roundabouts. Then, from observing the videos, the values of entry flow ($Q_{in}$) and conflicting circulating flow ($Q_{conf}$) are obtained for every 15 minutes of peak and off-peak times as well as the proportion of the drivers that experience no stopping at the entry (speed profile I, $P_I$) and multiple stopping (speed profile III, $P_{III}$), number of stops the vehicles experience for speed profile (III) and queue length. The proportion of vehicle with speed profile (II), $P_{II}$, is then calculated from the values of speed profile (I) and speed profile (III). Then the values of sum of conflicting flow and entry flow ($Q_{in} + Q_{conf}$) are plotted against $P_I$, $P_{II}$ and $P_{III}$ to develop predicting models of the percentage of occurrence of the three speed profiles (I, II, III) as a function of sum of conflicting flow and entry flow ($Q_{in} + Q_{conf}$) for two-lane roundabouts.

**Emission Estimation**

The “Vehicle Specific Power” (VSP) is the mechanical power used for the vehicle’s motion and is defined as the instantaneous power per unit mass of the vehicle (14) which influences the emission from vehicles. Frey et al. (5) developed a “modal binning approach” for calculating the vehicle emission from VSP based on speed, acceleration and power demand. The modal binning approach uses emission rates from on-board measurements of US light duty vehicles. The VSP reported as KW/metric-ton is estimated from equation 1:

$$VSP = v \left( 1.1a + 9.81 \sin \left( \arctan \left( grade \right) \right) + 0.132 \right) + 0.000302 v^3 \quad (Equation \, 1)$$

Where:

- $v =$ Instantaneous speed (m/s);
- $a =$ Instantaneous acceleration or deceleration (m/s$^2$);
- $grade =$ The terrain gradient (%).

Since VSP is a function of instantaneous speed and acceleration or deceleration rates, the three speed profiles will have distinctive effects on VSP function. Therefore, for calculating the hourly emission generated by vehicles entering the roundabouts different speed profiles (I, II and III) should be taken into account.
Table 1 Mean Values of Emissions for VSP Modes (15)

<table>
<thead>
<tr>
<th>VSP Mode</th>
<th>VSP Range (kW/ton)</th>
<th>NOx (g/s)</th>
<th>HC (g/s)</th>
<th>CO (g/s)</th>
<th>CO2 (g/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>VSP&lt;2</td>
<td>0.0001</td>
<td>0.0002</td>
<td>0.0011</td>
<td>0.966</td>
</tr>
<tr>
<td>2</td>
<td>-2≤VSP&lt;0</td>
<td>0.0001</td>
<td>0.0003</td>
<td>0.0015</td>
<td>1.343</td>
</tr>
<tr>
<td>3</td>
<td>0≤VSP&lt;1</td>
<td>0.0000</td>
<td>0.0002</td>
<td>0.0007</td>
<td>0.921</td>
</tr>
<tr>
<td>4</td>
<td>1≤VSP&lt;4</td>
<td>0.0002</td>
<td>0.0005</td>
<td>0.0023</td>
<td>2.351</td>
</tr>
<tr>
<td>5</td>
<td>4≤VSP&lt;7</td>
<td>0.0002</td>
<td>0.0007</td>
<td>0.0040</td>
<td>3.160</td>
</tr>
<tr>
<td>6</td>
<td>7≤VSP&lt;10</td>
<td>0.0003</td>
<td>0.0008</td>
<td>0.0046</td>
<td>3.940</td>
</tr>
<tr>
<td>7</td>
<td>10≤VSP&lt;13</td>
<td>0.0003</td>
<td>0.0010</td>
<td>0.0057</td>
<td>4.542</td>
</tr>
<tr>
<td>8</td>
<td>13≤VSP&lt;16</td>
<td>0.0004</td>
<td>0.0011</td>
<td>0.0057</td>
<td>5.103</td>
</tr>
<tr>
<td>9</td>
<td>16≤VSP&lt;19</td>
<td>0.0005</td>
<td>0.0012</td>
<td>0.0074</td>
<td>5.658</td>
</tr>
<tr>
<td>10</td>
<td>19≤VSP&lt;23</td>
<td>0.0006</td>
<td>0.0013</td>
<td>0.0066</td>
<td>6.081</td>
</tr>
<tr>
<td>11</td>
<td>23≤VSP&lt;28</td>
<td>0.0008</td>
<td>0.0013</td>
<td>0.0097</td>
<td>6.344</td>
</tr>
<tr>
<td>12</td>
<td>28≤VSP&lt;33</td>
<td>0.0009</td>
<td>0.0014</td>
<td>0.0143</td>
<td>7.012</td>
</tr>
<tr>
<td>13</td>
<td>33≤VSP&lt;39</td>
<td>0.0011</td>
<td>0.0015</td>
<td>0.0234</td>
<td>7.674</td>
</tr>
<tr>
<td>14</td>
<td>39≤VSP</td>
<td>0.0008</td>
<td>0.0016</td>
<td>0.0441</td>
<td>8.235</td>
</tr>
</tbody>
</table>

Table 1 shows the mean values for pollutants NOx, HC, CO2 and CO for VSP modes for a light-duty gasoline vehicle with odometer reading less than 50,000 miles and engine displacement less than 2.8 liters. These values are the average of tailpipe emissions measured from 10 light duty vehicles using Portable Emissions Measurement System (PEMS) at North Carolina State University, 2012 (15). Using the VSP methodology the hourly emissions generated by vehicles entering a roundabout approach is calculated from equation 2:

$$E_{Roundabout} = E_1 \cdot P_1 \cdot Q_{in} + E_{II} \cdot P_{II} \cdot Q_{in} + E_{III} \cdot P_{III} \cdot Q_{in}$$  \hspace{1cm} \text{(Equation 2)}

Where:

- $P_i$ = Proportion of vehicles for each speed profile $i = I, II$ and $III$;
- $Q_{in}$ = Entry flow rate (vph);
- $E_i$ = Emission associated with each speed profile.

The hourly emission of roundabout is estimated from the summation emission generated by each speed profile ($E_i$), multiplied by the proportion of those vehicles that spend on that speed profile ($P_i$) and the hourly entry flow of the roundabout ($Q_{in}$). In order to estimate the emission for each speed profile ($E_i$), second-by-second emission rates for the vehicle with that speed profile is calculated from VSP equation (equation 1).

Therefore $E_i$ is:

$$E_i = \sum_{n=1}^{N_i} EF_n$$  \hspace{1cm} \text{(Equation 3)}
Where:

- $EF_n =$ Emission factor (g/s) assigned to the n’th second of the speed profile based on the instantaneous VSP mode. The value of $EF_n$ for each pollutant is based on the VSP calculated for instantaneous speed (see Table 2);

- $Ni =$ Number of seconds in profile $i$;

- $E_i =$ Total emissions associated with each of the three profiles (i.e., $i = I, II$ or III).

In order to calculate $E_i$ a complete second-by-second vehicle dynamics for each speed profile is needed. For consistency among the three speed profiles, a constant value for the influence area of the roundabout should be defined. This influence area is the total distance that a vehicle decelerates from cruise speed as it approaches the roundabout, enters the circulating lane and accelerates as it exits the roundabout up to the point that reaches the cruise speed. For the purpose of analysis in this paper, the average influence area of all the runs through the four roundabout data collection sites was considered.
FIELD DATA COLLECTION

Site Selection

Figure 2 shows the aerial view of the data collection sites. The team chose four multilane roundabouts located on urban corridors with high traffic volume. One entry approach from each of these four roundabouts was studied by the use of overhead video cameras and GPS runs in different directions. Figure 2 marks the studied approach and the vehicle movement at each roundabout. Table 2 shows the location, inscribed diameter and average free flow speed and traffic volumes for each of the roundabouts.

Figure 2 Aerial View of the Four Data Collection Roundabouts, Aveiro, Portugal (Source: www.maps.google.com).

Figure 2

(a) Studied Approach

(b) Studied Approach

(c) Studied Approach

(d) Studied Approach
Table 2 Geometry Information for the Four Multilane Roundabout Data Collection Sites

<table>
<thead>
<tr>
<th>ID</th>
<th>Inscribed Diameter (m)</th>
<th>Entry Speed (km/h)</th>
<th>Exit Speed (km/h)</th>
<th>Entry Flow Rate (vph), Right Lane</th>
<th>Entry Flow Rate (vph), Left Lane</th>
<th>ADT (vpd)</th>
<th>Peak Hour Volume (vph)**</th>
<th>Circulating Flow (vph)</th>
<th>Circulating Width (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>58</td>
<td>35</td>
<td>42</td>
<td>295</td>
<td>218</td>
<td>6384</td>
<td>528</td>
<td>1114</td>
<td>8.3</td>
</tr>
<tr>
<td>b</td>
<td>47</td>
<td>34</td>
<td>31</td>
<td>216</td>
<td>192</td>
<td>5369</td>
<td>444</td>
<td>620</td>
<td>8.3</td>
</tr>
<tr>
<td>c</td>
<td>56</td>
<td>33</td>
<td>43</td>
<td>268</td>
<td>224</td>
<td>18742</td>
<td>550</td>
<td>492</td>
<td>8.2</td>
</tr>
<tr>
<td>d*</td>
<td>97/70</td>
<td>37</td>
<td>34</td>
<td>288</td>
<td>220</td>
<td>8803</td>
<td>728</td>
<td>1150</td>
<td>10</td>
</tr>
</tbody>
</table>

*Roundabout d is an oval roundabout therefore there are two values for inscribed diameter

** In the city of Aveiro, the traffic volume at peak hour is about 8.27% of ADT.

Data Collection

This research applied field data collection methodologies to acquire traffic characteristics of multilane roundabouts. The data collection has two main parts: 1) analysis of video data collected from four multilane roundabout approaches during afternoon peak hours and 2) obtaining second-by-second vehicle dynamics data of a Toyota Auris Hybrid making various turning movements at the roundabouts.

The research team used a QSTARZ GPS Travel Recorder (16) to record the second-by-second speed of the vehicle based on the latitude and longitude of the vehicle location in the roundabout. Along with the GPS, the team used a 8226B CarChip Pro by Davis Instruments which is an On-Board Diagnostic (OBD II) and it is compatible with passenger cars and light duty trucks (17). The car chip records second-by-second vehicle dynamics such as vehicle speeds, distance traveled and acceleration and braking rates. It also records additional engine performance measures. For each data collection trips the vehicle was equipped with the OBD II, GPS and video camera. Later in the transportation laboratory the team coordinated the data from OBD II and GPS to check the vehicle dynamics; speed, acceleration rate and breaking needed for analysis.

The research team installed overhead video cameras to capture entry traffic flow and conflicting circulating traffic flow in order to get the proportion of three speed profiles based on congestion level of the roundabout. A Bushnell Speedster speed gun was used to get a sample measurement of the speed of the vehicles in order to estimate average speed of the vehicles entering and exiting the roundabout under free flow conditions (18). The speeds exhibited in Table 2 are the average of 30 free flow speeds collected at entry and exit approaches of each roundabout. The speeds are collected with a radar speed gun at the time that a vehicle approaches the crosswalk with free flow speed while no platooning or no pedestrians are present.

RESULTS

Characteristic Speed Profile Predictive Models

From over 10 hours of video data collected from the four roundabout approaches, approximately 2 hours and a half at each location on weekdays during normal traffic conditions, the proportion of vehicles entering the roundabout in each speed profile I and III for each left and right lane were identified and extracted. Based on every 15-minute video observations the authors plot the percentage of vehicles that did not stop and stopped multiple times against the sum of entering and circulating flow. The percentage of vehicles with speed profile II is the difference in percentage of vehicles with speed profile I and III.
from 100%. As noted before the type of speed profile is highly related to the congestion level at the roundabout. Therefore the proportion of vehicles in each speed profile is plotted against the sum of entry flow \(Q_{in}\) and conflicting flow \(Q_{conf}\). Various regression models were tested to identify the predictive regression models with a good fit for the observations for each speed profile. Figure 3 shows the predictive regression models for the relative occurrence of speed profiles I and III, both for right and left lanes. The relative percentage of vehicles that enter the roundabout without stopping decreases as either the hourly entry or circulating flow of traffic increases. For values less than 500 vph for sum of entry and circulating flow, almost all vehicles enter the roundabout without any stopping. The percentage drops as the flow increases and according to the experimental data almost all vehicles had to stop at least once before entering the roundabout as the flow increases. The \(R^2\) for regression model developed for speed profile I is 0.66 for the right lane (0.62 for left lane) which means the model explains about 66% of the variability in the data. Vehicles which enter the roundabout with hourly flow \(Q_{in} + Q_{conf}\) greater than 500 vph experience at least one stop and the number of stop and go cycles will increase as their hourly flow increases\(Q_{in} + Q_{conf}\). Almost 50% of the vehicles that enter the roundabout with flow rates higher than 1500 vph will stop multiple times according to Figure 4c. The \(R^2\) value of the predictive regression model for vehicles with multiple stop-and-go cycles is 0.75 for right lane and 0.78 for left lane. However, the \(R^2\) value for the experimental model for vehicles with speed profile II is about 0.21 for both lanes. It should be noted that lane utilization rates of either of the two lanes at entry have an impact on the portion of the vehicles in different speed profiles observed at a two-lane roundabout. Therefore the models should be calibrated for each location based on lane utilization rates and lane configurations.
Figure 3 Predictive Models for Relative Occurrence of Speed Profiles: (a) I – Right Lane; (b) I – Left Lane; (c) II – Right Lane; (d) II – Left Lane; (e) III – Right Lane; (f) III – Left Lane.
Trajectories for Each Speed Profile

The type of the speed profile that occurs for a vehicle entering the roundabout is related to the congestion level (both entry and conflicting flow). The observation of the overhead video cameras from four roundabouts showed that even if the approach flow rate of the roundabout is very low, vehicles still experience multiple stops and very high accelerations when the circulating traffic is very high. It is also observed that vehicles on left lane and right lane face different circulating flows. Therefore the team chose two sets of speed profiles (I, II and III) for left and right lane separately to test the difference in emissions in these lanes. These speed profiles are the representative average speed trajectories for left and right lane using multiple field data GPS runs collected through the studied roundabouts. Figure 5 shows the speed trajectories for each of these conditions.

These speed trajectories are later used to estimate the emission generated from the roundabout. Figure 5 also demonstrates the total seconds spent in each VSP mode for each speed profile. On average the vehicles spend most of the times approaching the roundabout and waiting in queues to enter the circulating lane in modes 3 and 4. The percent of time spent in VSP mode 4 for the left lane is on average higher across the three different speed profiles compared to right lane. This suggests that the vehicles on the left lane have more gradual and moderate acceleration and deceleration rate through the speed trajectories versus the vehicles in the right lane which have sharper changes in speed. The speed trajectories in Figure 5 confirm the findings. It should be noted that for speed profile II, a vehicle traveling in left lane on average experiences longer stops compared to a vehicle traveling in right lane. This explains the longer time spent in mode 3 for left lane vehicle.
Figure 4 Average speed trajectory over distance for each Speed Profiles, each condition and total seconds spent in each VSP mode for each Speed Profile: (a) I; (b) II; (c) III.

Emissions Rates

This section uses the findings of previous sections to calculate and compare the emissions generated from left lane and from right lane for each speed profile I, II, and III. Based on different values for entry flow and conflicting circulating flow the percentage of the vehicles that have any of the three speed profiles are identified from Figure 4 for left lane and right lane separately. Then for each second-by-second speed trajectory provided in Figure 5 the total emissions for each speed trajectory in each lane is calculated using Equation 1. The total emissions for each approach lane are determined using Equation 2 and Equation 3.
However, in order to compare the emissions value for right lane and left lane, the authors defined several scenarios. These scenarios are based on the video observations of flow and lane utilization in two-lane roundabouts and the hypothesis of this paper. These scenarios are:

a) Different flow rates in left and right lane effects the emissions for each lane;

b) It is assumed that the vehicles in right lane face lower conflicting flow (flow from the nearest circulating lane) compared to vehicles in left lane which face higher conflicting flow (flow from both circulating lanes) and this observation might affect the emission for each lane;

c) High congested and low congested traffic periods may have different effects on emissions of left and right lane.

In order to test these hypotheses 8 different scenarios have been developed. These scenarios are shown in Table 3.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>a) Entry flow for: Right Lane/Left Lane (vph)</th>
<th>b) Conflicting flow for: Right Lane/ Left Lane (vph)</th>
<th>c) Total traffic congestion</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>symmetric 100/100</td>
<td>symmetric 700/700</td>
<td>low</td>
</tr>
<tr>
<td>2</td>
<td>symmetric 300/300</td>
<td>Symmetric 1200/1200</td>
<td>high</td>
</tr>
<tr>
<td>3</td>
<td>symmetric 100/100</td>
<td>Higher for left lane 500/800</td>
<td>low</td>
</tr>
<tr>
<td>4</td>
<td>symmetric 300/300</td>
<td>Higher for left lane 900/1200</td>
<td>high</td>
</tr>
<tr>
<td>5</td>
<td>higher in right lane 150/50</td>
<td>Symmetric 700/700</td>
<td>low</td>
</tr>
<tr>
<td>6</td>
<td>higher in right lane 400/200</td>
<td>Symmetric 1200/1200</td>
<td>high</td>
</tr>
<tr>
<td>7</td>
<td>higher in right lane 150/50</td>
<td>Higher for left lane 500/800</td>
<td>low</td>
</tr>
<tr>
<td>8</td>
<td>higher in right lane 400/200</td>
<td>Higher for left lane 900/1200</td>
<td>high</td>
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</tbody>
</table>

Figure 5 shows the comparison of emissions (g) per vehicle for condition in each lane for CO2. Other pollutants showed similar trends. Figure 5 illustrates for low flow rate conditions the emission of a vehicle traveling in right lane is higher than a vehicle traveling in left lane (21% to 43% higher). The reason is under low congestion level the vehicles mostly have speed profiles I or II (see Figure 4). Speed profiles I and II in right lane have higher speeds and sharper acceleration and deceleration rates (see Figure 5a and b) which cause higher emission rates. For high flow rate scenarios the emission from left lane is higher than right lane (9% to 12%, except for scenario 6). Because in high flow rate scenarios vehicles have mostly speed profiles II or III (see Figure 4). Speed profile III for left lane has longer stop-and-go cycles which results in higher emission rates. Overall other conditions such as difference in left lane and right lane flow and conflicting flow does not have an effect on emission rate (g) per vehicle.
The emission values in Figure 6 are determined by using the emission rates in Figure 5 for each scenario and multiplying them by the entry flow rate provided in Table 3 to estimate total emission (g) per hour.

Intuitively the emission rates for high congestion levels are higher compared to low congestion levels. Figure 6 shows that if left and right lane have equal flow rates (symmetric lane flow), during high congestion periods vehicles traveling in left lane emit more amount of pollutant (11% higher) than vehicles traveling in right lane (scenarios 1-4, vice versa for low congestion levels). However where flow
rate for left and right lane are not equal (assuming higher flow for right lane, scenarios 5-8), vehicles traveling in right lane produce more emission than vehicle traveling in the left lane (approximately 100% more) and the amount is not sensitive to any other conditions such as conflicting flow or congestion level. Analyses of the pollutants associated with traffic such as CO, HC and NOx resulted in same conclusions as the CO₂ emissions.

DISCUSSION, APPLICATION AND LIMITATIONS

This research introduced a methodology and framework to measure the emissions of multilane roundabouts. The paper explored the effect of multilane roundabouts located on urban corridors on pollutant emissions generated from vehicles. It further compared the emission of vehicles moving through the roundabout as they utilize either left or right lanes.

The methodology presented in this research can be generalized to estimate the emissions of roundabout footprints. Emissions are generally measured using VSP methodology. From the VSP formula presented in equation1, emission depends on grade, speed and changes in speed (acceleration/deceleration rates). Grade is a characteristic of each site. Since the study locations in this paper where located on relatively flat grades (less than 3%) the effect of that is ignored. In order to measure overall emissions per hour, the methodology consists of the following three steps:

1- Developing regression models estimating the percentage of total vehicles entering the roundabout experiencing each trajectory type I, II and III (regression models in Figure 2);
2- Finding a representative speed profile for each lane and for each trajectory type (since entry free flow speeds of the roundabouts have similar values, one representative is chosen among all profiles available from all study locations for each trajectory type);
3- Calculating the VSP distribution for each representative trajectory type (indentified from step 2);
4- Calculating the total emissions per hour by using the regression models to estimate the number of vehicles(proportion of entry volume) with each speed profile per hour (step 1), and multiply it by the corresponding VSP for each trajectory type.

The researchers can apply the methodology and models in this paper by measuring a roundabout’s flow characteristics (entry and circulating) and identifying a representative second-by-second speed profile for each trajectory type at the roundabouts. Step one, by knowing the entry and circulating flows, the researchers will be able to use the predictive regression models in this paper to estimate the proportion of vehicles that experience each trajectory type in an hour. Step two, by indentifying the representative speed profiles, the researchers will be able to calculate the VSP distribution of each trajectory type per vehicle. The total emissions per hour are then calculated using the results of step one and step two (multiplying the volume and percentage of each trajectory type by the emissions values per vehicle and summing up the results of the three trajectory types).

Previous research by Coelho et al. (4) compared and combined the emissions for roundabouts in Lisbon, Portugal and Raleigh North Carolina. Therefore, it can be argued that the findings of this paper are transferable to other roundabouts in Portugal or other cities and countered. However, one of the limitations of this paper is the small sample size of four roundabouts that we chosen for this study. Another limitation is similar approach speeds, approach geometries and traffic volumes for the four roundabouts studied for this research. Therefore future work is needed to enhance and calibrate the
predictive regression models in this paper and test the differences between traffic attributes of left and right lanes.

The findings of this paper shows that under low congestion levels vehicles in right lane emit more pollutant because they have on average higher speeds and sharper acceleration and deceleration rates. For high congestion levels if flow rates for left and right are equal, vehicles in left lane produce more emission because vehicles in left lane experience longer stop-and-go cycles and have different speed trajectory than vehicles in right lane.

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