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Driving around turbo-roundabouts vs. conventional roundabouts: Are there advantages regarding pollutant emissions?

P. Fernandes a, S. R. Pereira a, J. M. Bandeira a, L. Vasconcelos b, A. Bastos Silva c, and M. C. Coelho a

(a) University of Aveiro, Centre for Mechanical Technology and Automation / Department of Mechanical Engineering, Campus Universitário de Santiago, 3810-193 Aveiro, Portugal

(b) Polytechnic Institute of Viseu / Centre for Territory, Transport and Environment (CITTA), 3504-510 Viseu – Portugal

(c) University of Coimbra, Dept. Civil Engineering / Centre for Territory, Transport and Environment (CITTA), Rua Luís Reis Santos - Pólo II, 3030-788 Coimbra – Portugal

CONTACT P. Fernandes paulo.fernandes@ua.pt Centre for Mechanical Technology and Automation/ Department of Mechanical Engineering, University of Aveiro, Campus Universitário de Santiago, 3810-193 Aveiro, Portugal

Abstract

This paper addresses the impact of turbo-roundabouts located in urban areas on pollutant emissions using field measurements of vehicle activity data and road congestion levels. The research also compares the emissions of vehicles moving along a turbo-roundabout and a conventional multi-lane roundabout. Based on field measurements taken at turbo-roundabouts...
without curb dividers located in Grado (Spain) and multi-lane roundabouts in Aveiro (Portugal), three representative speed profiles for each speed trajectory were identified: no stop (I), stop once (II), and multiple stops (III). This study also develops discrete models for turbo-roundabouts and multi-lane roundabouts in which the relative occurrence of those speed profiles is expressed as a function of the entry and conflicting traffic flows. The Vehicle Specific Power (VSP) methodology is then employed to estimate second-by-second pollutant emissions.

This study tests the hypotheses that emissions are impacted by the differences in: 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).

Considering the selected case studies and traffic demands, vehicles at turbo-roundabouts generated more emissions (15-22%, depending on the pollutant) than multi-lane conventional roundabouts, especially under medium and high congested levels. These findings suggest that there are no advantages in implementing turbo-roundabouts from an environmental point of view, even in no saturated conditions.

**Keywords**

Turbo-roundabouts; Multi-lane roundabouts; Speed Profiles; Discrete Models; Emissions
1. Introduction and research objectives

Multi-lane roundabouts can handle larger volumes of traffic than single-lane roundabouts. However, they have some drawbacks such as allowing vehicles to negotiate the roundabout at higher speeds and enabling lane changing and weaving maneuvers at the circulatory ring and exit areas, leading to higher traffic conflicts (Bastos Silva 2004).

The turbo-roundabout concept was developed to address these problems, as an alternative of the conventional multi-lane roundabouts where drivers are required to choose their intended destination before entering the roundabout. The ring carriageway contains continuous spiral paths in which the entry, the circulating and the exit lanes are usually separated by curbs. Such raised curbs eliminate the conflicting points caused by weaving maneuvers and control the vehicle speeds (Fortuijn 2009).

The first turbo-roundabouts were constructed in the Netherlands, in 2000 (CROW 2008, Haskoning 2009). Since then, turbo-roundabouts have been increasingly used in several European countries including Germany (Brilon 2011), Slovenia (Tollazzi, Rencelj, and Turnsek S. 2011, Tollazzi and Rencelj 2014), and most recently in Spain (Bulla and Castro 2011). Awareness about this layout is also growing in the United States (US) (Trueblood 2011) and Italy. Their design features are usually based on the Dutch guidelines (CROW 2008, Haskoning 2009).

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

A typical concern with the use of turbo-roundabouts is their impact in terms of capacity. Figure 1
illustrates a conventional roundabout (four double-lane entrances and four double-lane exits) and
a turbo-roundabout of similar size (four double-lane entrances, two double-lane exits and two
single-lane exits). The turbo-roundabout was aligned assuming direction AC as a major
direction, and provides two entry lanes for these movements. The main differences that affect
capacity are (Fortuijn 2009):

1. On a conventional roundabout, the outer circulatory lane at the major entrances (A and C)
is used by a fraction of the through movements (DB and BD); on a turbo-roundabout, the
opposing traffic is concentrated in a single lane, which reduces the frequency of large
gaps and leads to a decrease in capacity;

2. On a conventional roundabout, drivers in the outer lane (adjacent to the sidewalk) of the
minor entrances (B and D) are affected by all circulating vehicles, even if the trajectories
do not actually intersect; on a turbo-roundabout, the outer lane is used only for right-turn
(BC and DA movements) and the opposing traffic is reduced since part of the through
traffic is physically separated at the exit;

3. While right-turning traffic must use the outer entry lane on the conventional roundabout
(BC and DA movements), both the inner and outer lanes can be used at the minor
entrances of a turbo-roundabout.
The differences in layouts are also reflected in vehicle speeds. The spiral lanes associated with raised dividers define high curvature paths, forcing a slow approach and circulating speeds. These design considerations have a significant effect on intersection capacity and can also affect pollutant emissions.

Figure 1 Differences between roundabout layouts: a) Multi-lane roundabout; b) Turbo-roundabout.

This work introduces a methodology that can explore the effect of turbo-roundabout operations on pollutant emissions and capacity. The methodology described in this study is built on previous studies (Coelho, Farias, and Rouphail 2006, Salamati et al. 2013) which were dedicated to the environmental impacts of conventional single (Coelho, Farias, and Rouphail 2006) and multi-lane roundabouts (Salamati et al. 2013). It is hypothesized that emissions and capacity are impacted by the differences in: 1) the characteristics of the speed profiles; 2) the volumes of entry and conflicting flows; 3) the overall saturation level; and 4) the adopted layout (multi-lane vs. turbo-roundabout).

The research uses an approach founded on experimental measurements of traffic characteristics and saturation levels in real turbo-roundabouts to predict the relative occurrence of each speed profile that vehicles experience as they travel through the turbo-roundabout. These speed profiles are: no stop (I), stop once (II) and multiple stops (III) at the entry of the roundabout. Emissions
are then estimated using the Vehicle Specific Power (VSP) methodology (USEPA 2002), which is based on on-board measurements in light passenger vehicles (LPV).

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

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

Section 2 presents a review of the technical literature. The methodology used in this research is explained in Section 3. Results are presented and discussed in Section 4, followed by the main conclusions and research limitations in Section 5.
2. Literature Review

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

From the literature, it is clear that there is still no consensus about the benefits of turbo-roundabouts regarding the available capacity of the intersection. The first studies carried out (Yperman and Immers 2003, Engelsman and Uken 2007) showed that turbo-roundabouts achieved higher capacity than traditional roundabouts with similar design features. Other authors (Giuffrè, Guerrieri, and Granà 2009, Mauro and Branco 2010, Giuffrè, Granà, and Marino 2012, Silva, Vasconcelos, and Santos 2014) recognized that the relative performance of turbo-roundabouts was largely dependent on the local traffic conditions and layout. Corriere and Guerrieri (2012) explain that, for each site, the pedestrian presence, conflicting traffic flows, lane capacity, driver behavior, balance of the traffic demand on each approach, and the traffic flow balance at the circulating lanes will affect each approach capacity and vehicle delay at turbo-roundabouts. Vasconcelos, A. B. Silva, and Seco (2014) proposed a new lane-based capacity methodology to assess the capacity of a turbo-roundabout based on gap-acceptance theory. The authors stated that the turbo-roundabout only achieved capacity levels comparable to the traditional two-lane layout when the proportion of right turns at the minor entrances was very high.
However, the safety benefits of turbo-roundabouts are consensual in almost all previous studies confirming their advantages over the multi-lane layout (Fortuijn 2009, Silva, Vasconcelos, and Santos 2014, Mauro and Cattani 2010).

Although extensive, the current macroscopic (e.g. EMFAC, COPERT or Transport Emission Model for Line Source – TREM), mesoscopic (e.g. aaTraffic Signalized and unsignalized Intersection Design and Research Aid – aaSIDRA) and microscopic emission models (e.g. Virginia Tech Microscopic Energy and Emission – VT-MICRO, Comprehensive Modal Emissions Model – CMEM, VSP, MOtor Vehicle Emission Simulator – MOVES or EnViver) have limited applications in roundabout case studies.

The TREM and COPERT models, for instance, are not suitable for micro scale impacts estimation of roundabouts since they assume that emission rates are constant for different speed ranges (Borrego et al. 2003, Katsis and Ntziachristos 2012). EMFAC is tailored to the Californian reality (Pierce et al. 2008). By far the most widely recognized roundabout traffic model is aaSIDRA which contains vehicle emissions estimates based on a “four-mode elemental model”: deceleration, idle, acceleration and cruise. However, aaSIDRA does not include the impact of stop and go cycles (Akçelik&Associates 2013).

Alternatively, microscopic models estimate instantaneous vehicle fuel consumption and emission rates, which are aggregated to estimate network-wide measures of effectiveness. These models are sensitive to changes in vehicle acceleration behavior and thus can be used in the evaluation of operational-level transportation projects such as roundabouts. One widely used microscopic approach is the estimate of emissions through the concept of vehicle specific power (VSP). The on-board vehicle activity and emissions are acquired by a portable emissions measurement
system (PEMS) that assesses emissions under real-world conditions at any location by vehicles on a second-by-second basis (Frey, Zhang, and Rouphail 2008). VSP is highly correlated with emissions since it overcomes the fact that the cruise mode has a fixed factor independent of speed; it includes the impact of different levels of accelerations and speed changes on emissions, and it accounts for the effect of road infrastructure on power demand (Kutz 2008).

A good deal of research has documented the effective use of the VSP methodology to estimate the emissions of vehicles at different roundabout layouts (Coelho, Farias, and Rouphail 2006, Salamati et al. 2013, Anya et al. 2013, Mudgal et al. 2014, Vasconcelos et al. 2014). Coelho, Farias, and Rouphail (2006) identified three characteristic of speed profiles for a vehicle approaching single-lane roundabouts: (I) no stop; (II) stop once and (III) multiple stops. They also found that the relative occurrence of these profiles was dependent on the entry and conflicting traffic flows. Based on these findings, the same authors developed regression models to describe the relative occurrence of these speed profiles for approaching vehicles at single-lane roundabouts. Based on this research, Salamati et al. (2013) developed similar regression models in each approaching lane (right vs. left) at multi-lane roundabouts. Anya et al. (2013) explored the environmental benefits posed by the conversion of a signalized intersection into a two-lane roundabout in an urban corridor in Raleigh, North Carolina. They found that the implementation of the roundabout was only relevant at the intersection-level in the right turn movements from the minor street to the main street. Mudgal et al. (2014) demonstrated that acceleration events in the circulating and exiting areas of a roundabout contributed to more than 25% of the emissions for a given speed profile.
The assessment of turbo-roundabouts with respect to certain impacts is relatively unknown. Vasconcelos et al. (2014) used microsimulation models to evaluate and compare the performance of a single-lane roundabout, in Coimbra, Portugal, and modeled a two-lane roundabout and a turbo-roundabout in terms of capacity, safety and emissions. The results showed that the turbo-roundabout reached higher saturation levels and delays than two-lane roundabout, especially under high proportions of left turns (more than 60%). Concerning emissions, carbon dioxide (CO$_2$) and nitrogen oxides (NO$_X$) were higher for the turbo-roundabout, regardless of the proportion of turning movements and/or traffic flows at each approach.

More recently, Tollazzi et al. (2015) introduced a methodological framework to compare capacity and vehicle delays as well as CO$_2$, NO$_X$, and particulate matter of less than 2.5μm (PM$_{2.5}$) and 10μm (PM$_{10}$) at different roundabout layouts: target, four-flyer, flower and conventional. The authors found that under medium-high entry traffic volumes (~2,800–3,000 vehicles per hour – vph) the target roundabout offered lower costs than the other intersections. However, the analysis did not include field measurements of turbo-roundabouts.

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

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

This study is an empirical approach based on field measurements of the vehicle dynamics and the overall congestion level. The methodology overview is depicted in Figure 2. Input data such as entry and conflicting traffic flows, queue length and stop-and-go cycles were collected by overhead video cameras installed at the roundabouts (turbo-roundabouts and multi-lane roundabouts). Vehicle activity data such as second-by-second instantaneous speed, acceleration-deceleration and road slope (grade) were collected using a Global Positioning System (GPS) data logger and On-Board Diagnostic (OBD) system. The relationship between congestion level of roundabouts and occurrence of each speed profile was then established, using discrete choice models (Ben-Akiva and Lerman 1985). After that, the VSP methodology was used to estimate CO₂, carbon monoxide (CO), NOₓ and hydrocarbons (HC) emissions. Finally, the discrete choice models obtained from turbo and multi-lane roundabouts were compared. The following sections describe the methodological steps in detail.

Figure 2 Methodology Overview.

3.1. Site Selection

Two sets of roundabouts were selected for this study – three multi-lane roundabouts and three turbo-roundabouts. Figure 3 shows the aerial view of the data collection sites as well as the
studied approaches. Three turbo-roundabouts on the N-634 national road in the city of Grado, Spain were selected, as shown in Figure 3 (a-c). These turbo-roundabouts were selected because there are no layouts of this type in Portugal. Iberian case studies are therefore represented. These turbo-roundabouts were constructed and started operating in 2009 (Bulla and Castro 2011).

The through movement from the northeast-bound approach was studied using GPS and OBD runs in different directions. That approach has two entry lanes from 200 meters to the yield line of the turbo-roundabout. The right lane only provides movements to the first exit while the left lane allows the remaining movements. The multi-lane roundabouts, displayed in Figure 3 (d-f), are located 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. The sites’ characteristics such as location, circulating width, the average approach speed, and the speeds at the entrance and exit lanes of the roundabouts are summarized in Table 1. The morning entry and conflicting traffic flows are also provided.

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

**Figure 3** Aerial View of the three data collection turbo-roundabouts, Grado, Spain: a) TR1; b) TR2; c) TR3 and multi-lane roundabouts, Aveiro, Portugal: d) ML1; e) ML2; f) ML3.
Table 1 Key characteristics of the selected roundabouts.

3.2. Data Collection

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

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

The duration of the video recording was obtained using statistical significance tests to enable the estimation of a 95% confidence interval in relation to the average and standard deviation of the traffic stream parameters. Entry and conflicting traffic flows, queue lengths and the number of stop-and-go situations were recorded by overhead video cameras installed at two strategic points on the roundabouts, as illustrated in Figure 3. The first camera recorded all vehicle paths through
the roundabouts; the second camera, which was installed on the central island, recorded the queue lengths at the selected entrances.

The estimated instantaneous speed and acceleration-deceleration profiles were derived from experimental data on vehicle dynamics using an LPV conforming to Euro V Emission Standard equipped with a GPS and OBD to make several turning movements at the roundabouts. The vehicle has the following characteristics: year – 2013; mileage – 5,700 km; engine size – 1.5L; maximum power – 81 kW at 4,000 rpm; torque – 1,750 rpm; transmission type – 5-speed manual gearbox; gross vehicle weight – 1,210 kg. These characteristics are within the tested LPV specifications that were used to obtain the emissions factors for VSP methodology. The test vehicle is also representative of the LPV category in Europe (ICCT 2014).

The QSTARZ GPS Travel Recorder (Qstarz 2012) was used to capture second-by-second vehicle speed and the selected sites’ characteristics (road grade, latitude and longitude). The CarChip Fleet Pro OBD sensor was used in coordination with the in-vehicle GPS to record the vehicle speed, distance travelled and deceleration-acceleration rates in 1-second intervals (Davis Instruments 2012). To coordinate the equipment, the research team powered off the vehicle between travel movements to and from the roundabout (in locations outside the influence area of the study locations).

A total of 240 GPS travel runs of through movements (approximately 40 at each location) were identified and extracted for this research (approximately 400 km of road coverage over the course of 15 hours). According to Li et al. (2002), for a significance level of 5%, the above number of runs (sample size) per location was considered to be suitable to generate reliable results from the data acquired.
To reduce systematic errors, 3 drivers (all male, aged 25 to 35 with varying levels of driving experience) performed the same number of trips (approximately 40) for each roundabout movement. Concurrently, over 21 hours of video data (total of 84 data samples of 15 minutes) were gathered from the six roundabout approaches (approximately 3.5 hours at each location). These series of measurements were sufficient to enable the estimation of a 95% confidence interval in relation to the average and standard deviation of the measured parameters.

3.3. Characteristic Speed Profiles

Based on vehicle activity, and patterns in speed profiles, vehicles experience three different speed profiles (Figure 4 a-c) as they approach a generic roundabout (multilane or turbo), as demonstrated by previous studies (Coelho, Farias, and Rouphail 2006, Salamati et al. 2013). It should be noted that the relative occurrence of each profile is highly dependent on the level of congestion of the approach (Coelho, Farias, and Rouphail 2006, Salamati et al. 2013). The three speed profiles represent:

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

II. A vehicle decelerates while approaching the roundabout, comes to a complete stop at the yield line to enter in the circulating stream and finds a crossable gap, then accelerates to enter the circulating ring and exits the roundabout;
III. A vehicle that experiences several stops on the approach as it moves up the queue to reach the yield line, and then accelerates to enter the circulating ring and leaves the roundabout.

**Figure 4** Typical speed profiles through turbo-roundabout and multi-lane roundabout (from the left entry lane): a) speed profile I; b) speed profile II and c) speed profile III.

The main goal of this research is to quantify the relationship between the congestion levels of the roundabouts and the percentage of vehicles that experience each speed profile. These levels of congestion are expressed indirectly as the sum of the entry ($Q_{in}$) and conflicting traffic flows ($Q_{conf}$) at each entry lane (Coelho, Farias, and Rouphail 2006). Video cameras are used to capture the vehicle movements at the entry and circulating lanes of the selected roundabouts. $Q_{in}$ and $Q_{conf}$ are both obtained for every 15 minutes of morning and afternoon peak periods. The proportion of the drivers that do not stop at the entry ($P_I$), experience one complete stop ($P_{II}$) and multiple stopping ($P_{III}$) are also extracted from the recordings.

3.4. **Discrete Choice Models**

As mentioned before, the main goal of the proposed model is to identify the relative occurrence of each speed profile based on prevailing congestion levels. By selecting three speed profiles ($P_I$, $P_{II}$ and $P_{III}$), it was intrinsically considered a discrete choice process. Discrete choice models are based on the theory of stochastic utility whereby a decision maker makes a choice in order to
maximize the utility function. This utility function, shown in Equation (1), is constructed as a combination of known explanatory variables, the systematic part of utility, and a random part which is unknown (Ben-Akiva and Lerman 1985).

\[ U_{i,n} = V_{i,n} + \varepsilon_{i,n} \]  

Where:

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

Assuming that the error term of the utility expression is logistically distributed, the multinomial logit model (MNL) is then obtained from Equation (2) (Correia and Silva 2010):

\[ P_n(i) = \text{Probability}(U_{i,n} > U_{j,n}) = \frac{e^{V_{i,n}}}{\sum_{j\in C_n} e^{V_{j,n}}} \]  

(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 (Coelho, Farias, and Rouphail 2006). Since only differences in utility maker in influencing the choice, the outcome “\( P_1 \)” (no stopping) was chosen as reference. The MNL probabilities for Profiles I, II and III are given by Equations 3, 4 and 5, respectively:

\[
P(Y = " P_1 ") = \frac{1}{1 + e^{\beta_{2,0} + \beta_{2,1}Q_{total}}} + e^{\beta_{3,0} + \beta_{3,1}Q_{total}}
\]

\[
P(Y = " P_{II} ") = \frac{e^{\beta_{2,0} + \beta_{2,1}Q_{total}}}{1 + e^{\beta_{2,0} + \beta_{2,1}Q_{total}}} + e^{\beta_{3,0} + \beta_{3,1}Q_{total}}
\]

\[
P(Y = " P_{III} ") = \frac{e^{\beta_{2,0} + \beta_{2,1}Q_{total}}}{1 + e^{\beta_{2,0} + \beta_{2,1}Q_{total}}} + e^{\beta_{3,0} + \beta_{3,1}Q_{total}}
\]

Where the different \( \beta_{i,j} \) are the model parameters to be estimated from the sample data:

\( \beta_{2,0} \) and \( \beta_{2,1} = \) intercept and coefficient for outcome “Profile II”

\( \beta_{3,0} \) and \( \beta_{3,1} = \) intercept and coefficient for outcome “Profile III”
3.5. Emission Estimation

VSP is the mechanical power used for the vehicle’s motion and it is defined as the instantaneous power per unit mass of the vehicle. This instantaneous power generated by the engine is used to overcome rolling resistance and aerodynamic drag and to increase the kinetic and potential energy of the vehicle (Kutz 2008). This approach was selected since it can estimate instantaneous emissions based on second-by-second vehicle dynamics (speed, acceleration and grade) from instantaneous emissions data. VSP values are categorized in 14 engine regime modes, and an emission factor for each mode is used to estimate CO₂, CO, NOₓ and HC emissions for LPV (Frey, Zhang, and Rouphail 2008). Kolak et al. (2013) and Coelho et al. (2014) recognized that a VSP based emission model leads to a better estimation of vehicle emissions (Kolak et al. 2013) and regional air quality concentrations (Coelho et al. 2014) than an average speed-based emissions model.

For a typical LPV, VSP is estimated as (USEPA 2002):

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

(6)

Where:

\( VSP = \) Vehicle specific power (kW/ton);

\( v = \) Instantaneous speed (m/s);

\( a = \) Instantaneous acceleration or deceleration (m/s²);

\( grade = \) Terrain gradient (decimal fraction).
The average emission rates for pollutants CO\textsubscript{2}, CO, NO\textsubscript{X} and HC for each VSP mode for light passenger gasoline vehicles (LPGV), light passenger diesel vehicles (LPDV) and light commercial diesel vehicles (LCDV) are presented in Table 2. The LPGV values are the average tailpipe emissions from over forty LPV with engine size between 1.5 L and 2.5 L, gross weight from 1,070 kg to 2,086 kg, and mileage between 4,989 km and 368,186 km; the vehicle model years range from 1997 to 2012. The emissions were measured by a PEMS (Anya et al. 2013). The LPDV and LCDV emission rates can be found elsewhere (Coelho et al. 2009).

The authors tried to fit the emission rates as far as possible to the characteristics of local fleet compositions, i.e. the engine capacity, average age of vehicles and fuel type. Such emission rates can be applied to a European car fleet (Vasconcelos et al. 2014, Fontes et al. 2014) since they include a wide range of engine displacement values. The following distribution fleet composition was used for both roundabout layouts (ACAP 2014): 45% of LPGV, 34% of LPDV and 21% of LCDV. Analysis of the video footage showed a low number of heavy-duty vehicles (lower than 2%) in the selected case studies. Thus, they were not included in the emissions calculations.

| Table 2 Mean Values for CO\textsubscript{2}, CO, NO\textsubscript{X} and HC emission rates (g/s) for VSP modes for LPGV, LPDV and LCDV. |

Then the pollutant emissions per vehicle for the three speed profiles were aggregated to evaluate the overall impact of a change in the average path through the roundabout. Equation 7 provides...
the estimation of hourly emissions generated by vehicles entering a roundabout by using VSP methodology:

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

(7)

Where:

$$E_{TR} = \text{Hourly emissions at the turbo-roundabout (g)};$$

$$E_i = \text{Emission per vehicle associated with each speed profile } i = \text{I, II and III (g);}$$

$$P_i = \text{Proportion of vehicles that experienced each speed profile } i = \text{I, II and III;}$$

$$Q_{in} = \text{Entry flow rate (vph).}$$

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

$$E_{ij} = \sum_{m=1}^{N_m} F_{mj}$$

(8)

Where:

$$E_{ij} = \text{Total emissions for source pollutant (g);}$$
\( m \) = 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 are obtained from Equation 6. These speed profiles take into account the impact of the different traffic flow levels on the approach and circulating areas and thus on vehicle operating speed.

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

This section presents and discusses the main results from discrete models and characteristic speed trajectories for turbo and multi-lane roundabouts. The pollutant emission impacts (CO₂, CO, NOₓ and HC) of the two layouts are also compared.

4.1. Predictive Discrete Models

Two MNL models were obtained – one for multi-lane roundabouts and the other for turbo-roundabouts. The models were calibrated through maximum likelihood using SPSS software (see Table 3). The sample comprised 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 (P₁, P₁ or P₃) and total traffic flow (15 minute period).

Table 3 Calibrated coefficients for the MNL model.

Figure 5 illustrates the two calibrated MNL models. As expected, the probability of a driver being able to negotiate the roundabout without stopping (P₁) decreases as the total traffic flow increases. For values below 600 vph for the sum of entry and circulating flow, most vehicles enter the multi-lane roundabout without any stops. For the turbo-roundabout layout, this value
fell by 200 vph (400 vph). About 50% of the vehicles that enter the multi-lane and turbo-roundabout with flow rates higher than 1200 vph and 800 vph, respectively, face multiple stops. Therefore, the comparison of the two graphs shows that the probability for one or more stops ($P_{II}$ and $P_{III}$) for the same total traffic is higher in the turbo-roundabouts. This happens essentially because on the two-lane roundabouts the conflicting traffic is divided into two lanes, which increases the number of large gaps available for the vehicles waiting at the yield line (Vasconcelos, A. B. Silva, and Seco 2014). Concerning speed, there are no significant differences in the average approach speeds between roundabout layouts, as listed in Table 1. However, the differences in terms of conflicting traffic flows and roundabout geometry dictated some variation in the entry speeds at the yield line among the candidate case studies.

**Figure 5** Predictive models for the relative occurrence of speed profiles I, II and III: a) multi-lane 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 was found to depend on the prevailing traffic demand at the roundabout ($Q_{total} = Q_{in} + Q_{conf}$). The video data from the turbo-roundabouts showed that low circulating speed values (see Table 1 for those details) led to significant idle times and stop-and-go situations in the approach lane. Accordingly, the vehicle dynamics through the two layouts is rather different.
With this concern in mind, all the speed profile sets (I, II and III) for the turbo and multi-lane roundabouts were selected to assess the differences in emissions. The corresponding percentage of time in each VSP mode exhibited in Figure 6 (a-c) is the average speed trajectories for a turbo-roundabout and a multi-lane roundabout (from the left entry lane) using multiple sets of GPS field data (considering all performed runs and all drivers). These speed trajectories are later used to estimate emissions from the turbo-roundabout and multi-lane roundabout using the predictive regression models developed for each case.

Based on the raw distributions of VSP modes from the turbo-roundabout for speed profile I, vehicles spent most of the time in VSP modes 1, 2, 3, 4 and 5. This corresponds to decelerations as vehicles approach the turbo-roundabout (modes 1 and 2), enter the circulating lanes at low speeds or stop (mode 3) and accelerations as they exit the turbo-roundabout (modes 4 and 5). The percent of the time spent in VSP modes higher than 5 for the turbo-roundabout is slightly (≈3%) lower across the three speed profiles compared to multi-lane roundabout on speed profile I. This means, as expected, that vehicles at the turbo-roundabout experience lower speeds than those at the multi-lane layout (perhaps due to higher deflection level and low circulating speeds). Nevertheless, a vehicle travelling in turbo-roundabout faces more idle and low speed situations at the downstream and circulating areas than a vehicle travelling in a multi-lane roundabout, especially in speed profiles II and III. This is mostly because the lane dividers prevent drivers from using the full carriageway width to reduce curvature, which contributes to lower circulating speeds.
Figure 6 Total seconds spent in each VSP model (with 95% 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 the speed profiles I, II and III to calculate and compare the emissions produced by vehicles at a turbo-roundabout and a multi-lane roundabout. According to the different values of the entry and conflicting flows, the percentage of vehicles that experience any of the three speed profiles at a turbo-roundabout is identified from Figure 5. Next, the total emissions for each speed trajectory in each layout are calculated using Equations 6, 7 and 8.

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

- Scenario 1: \( Q_{in} = Q_{conf} = 100 \text{ vph} \) (\( Q_{total} = 200 \text{ vph} \));
- 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 footage of traffic flows on both roundabout layouts and the hypothesis of this study:

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

The comparison of hourly emissions per vehicle (g/veh/h) for the turbo-roundabout and multi-lane roundabout for CO$_2$, CO, NO$_X$ and HC is given in Figure 7. The results show that in both low and moderate congestion levels (scenarios 1-4) the pollutant emissions generated by vehicles at the turbo-roundabout are higher than those verified at the multi-lane roundabout (13%, 16%, 12% and 20% for CO$_2$, CO, NO$_X$ and HC, respectively). For high flow rates (scenarios 5-6), turbo-roundabouts yield even more emissions than multi-lane roundabouts (19%, 23%, 19% and 29% for CO$_2$, CO, NO$_X$ and HC, respectively). This is possible because of the longer stop-and-go cycles that vehicles experience at the turbo-roundabout since their speed profiles are mostly II (>$22\%$) or III (>$34\%$) in high flow rate scenarios.
On average, vehicles spent 23% more time crossing the turbo-roundabout than they spent on the multi-lane layout (assuming equal travel distances), which leads to higher emissions, as shown in Figure 6. This explains the similar yield trend in the CO₂, CO, NOₓ and HC graphs. The main conclusion from Figure 7 is that the time spent by vehicles as a result of the difference between cruise and circulating speeds has more impact on emissions at the turbo-roundabout than the deceleration-acceleration rates do (on average >7% over the multi-lane layout).

To sum up, the relative difference between emissions produced at the turbo and multi-lane roundabouts is not sensitive to the congestion level. These findings are in line with previous studies on turbo-roundabouts in which those layouts produced a higher amount of CO₂ and NOₓ emissions than multi-lane roundabouts (Vasconcelos et al. 2014).

**Figure 7** Hourly variation of the emissions per vehicle (g/veh/h) for different traffic scenarios (and 95% estimated confidence intervals): a) CO₂; b) CO; c) NOₓ; and d) HC.

**5. Conclusions**

This paper addressed the impact of turbo-roundabouts on pollutant emissions and used a methodology and framework based on field measurements of vehicle activity and traffic flow data to estimate the emissions. The emissions for vehicles travelling in turbo-roundabout and multi-lane roundabouts were also compared. The methodology estimated overall emission via the following steps:
1. Discrete models were developed to establish a relationship between distinct speed profiles (no stop, stop once and several stops) that vehicles experience at turbo- and multi-lane roundabouts and traffic conditions (entry and conflicting flows).

2. A representative speed profile was chosen for each trajectory, assuming that each roundabout layout had similar approach speeds.

3. The VSP distribution was calculated for each representative trajectory (identified from Step 2).

4. The hourly pollutant emissions were calculated from discrete models that estimated the proportion of entry volume for each speed profile occurrence (Step 1), and multiplied them by the corresponding VSP for each trajectory.

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

The major difference between the turbo and multi-lane layouts lies in the possibility of weaving and lane-change maneuvers in the circulating ring of the roundabout. The models developed in this work did not take into account those operational differences, but they were captured and reflected in the GPS runs.

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

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

Using a PEMS to collect field emissions on those sites or others with equivalent fleet composition would be useful and meaningful. This procedure would provide a validation of emission results and enhance the accuracy of the developed models.

Acknowledgements

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Figure 8 Differences between roundabout layouts: a) Multi-lane roundabout; b) Turbo-roundabout.
Figure 9 Methodology Overview.

- GPS Data Logger
  OBD Reader
- Video Recordings
- Second-by-second vehicle dynamics:
  instantaneous speed, acceleration, grade
- Entry traffic flow, conflicting traffic flow, queue length, stop-and-go
- Algorithm to determine the probability of characteristic speed profile occurrence
- No Stop Profile I
- One Stop Profile II
- More than one stop Profile III
- CO$_2$, CO, NOx and HC emissions for Light Passenger Vehicles, estimation for each profile,
  using VSP approach
- Aggregate emissions estimation
- Comparison between predictive discrete models for turbo-roundabouts and multi-lane roundabouts
Figure 10 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.
Legend: TR – Turbo-Roundabout; ML – Multi-lane Roundabout
Figure 11 Typical speed profiles through turbo-roundabout and multi-lane roundabout (from the left entry lane): a) speed profile I; b) speed profile II and c) speed profile III.
Figure 12 Predictive models for the relative occurrence of speed profiles I, II and III: a) multi-lane roundabouts; b) turbo-roundabouts.
Figure 13 Total seconds spent in each VSP model (with 95% confidence intervals) for each speed profile: a) I, b) II, c) III.

Legend: TR – Turbo-Roundabout; ML – Multi-lane Roundabout
Figure 14 Hourly variation of the emissions per vehicle (g/veh/h) for different traffic scenarios (and 95% estimated confidence intervals): a) CO$_2$; b) CO; c) NO$_X$; and d) HC.
Table 4 Key characteristics of the selected roundabouts

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

\(^a\) Average approach speed 150-200 meters from the circulatory ring of the roundabout.

\(^b\) Values observed at the entrance and exit lines.

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

\(^d\) Average values of traffic flows (all circulating lanes) observed for the morning peak period (8-9 a.m.).
### Table 5 Mean Values for CO₂, CO, NOₓ and HC emission rates (g/s) for VSP modes for LPGV, LPDV and LCDV.

<table>
<thead>
<tr>
<th>Vehicle Type</th>
<th>Definition (kW/ton)</th>
<th>VSP Mode</th>
<th>Average modal emission rates</th>
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</thead>
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<tr>
<td></td>
<td></td>
<td></td>
<td>CO₂</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(g/s)</td>
</tr>
<tr>
<td>Light Passenger Gasoline Veh.</td>
<td>VSP&lt; -2</td>
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<td>1.04</td>
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<tr>
<td>(LPGV)</td>
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<td>2</td>
<td>1.31</td>
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<tr>
<td></td>
<td>0 ≤ VSP &lt; 1</td>
<td>3</td>
<td>0.93</td>
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<tr>
<td></td>
<td>1 ≤ VSP &lt; 4</td>
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<td>2.17</td>
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<td></td>
<td>4 ≤ VSP &lt; 7</td>
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<td>3.00</td>
</tr>
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<td></td>
<td>7 ≤ VSP &lt; 10</td>
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<td>3.77</td>
</tr>
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<td>10 ≤ VSP &lt; 13</td>
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<td>4.47</td>
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<td>13 ≤ VSP &lt; 16</td>
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<td>16 ≤ VSP &lt; 19</td>
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<td>5.61</td>
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<td>23 ≤ VSP &lt; 28</td>
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<td>VSP ≥ 39</td>
<td>14</td>
<td>8.06</td>
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<td></td>
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<td>2.34</td>
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<td></td>
<td>7 ≤ VSP &lt; 10</td>
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<td>3.29</td>
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<td></td>
<td>VSP ≥ 39</td>
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<td>19.38</td>
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¹ As computed by Equation 6
Table 6 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>
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<tbody>
<tr>
<td>$P_{II}$</td>
<td>Intercept</td>
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<td>.17</td>
<td>276.3</td>
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<td></td>
<td>$Q_{total}$</td>
<td>.003</td>
<td>$\beta_{2,1}$</td>
<td>.00</td>
<td>86.3</td>
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<tr>
<td>$P_{III}$</td>
<td>Intercept</td>
<td>-7.55</td>
<td>.62</td>
<td>146.4</td>
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<td></td>
<td>$Q_{total}$</td>
<td>.008</td>
<td>$\beta_{3,1}$</td>
<td>.00</td>
<td>62.0</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Speed profile</th>
<th>x</th>
<th>B</th>
<th>Std. Error</th>
<th>Wald</th>
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<td>.006</td>
<td>$\beta_{3,1}$</td>
<td>.00</td>
<td>295.3</td>
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</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 ($X^2_w = B/SE$) that tests the null hypothesis that the constant equals 0. This hypothesis is rejected because the p-value (listed in the column "Sig.") is smaller than the critical p-value of 0.05.