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Transportation Research Procedia 3 (2014) 80 – 89

Transportation Research Procedia

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17th Meeting of the EURO Working Group on Transportation, EWGT2014, 2-4 July 2014,
Sevilla, Spain

# Driver behavior characterization in roundabout crossings

Ana Bastos Silva[a]*, Sílvia Santos[a], Luís Vasconcelos[b], Álvaro Seco[a], João Pedro Silva[c]†

[a]*University of Coimbra, Rua Luís Reis Santos, 3030-788 Coimbra, Portugal*
[b]*Polytechnic Intitute of Viseu, Campus Politécnico de Represes, 3504-510 Viseu, Portugal*
[c]*School of Technology and Management, Polytechnic Institute of Leiria, Campus 2,Morro da Len –Alto do Vieiro,2411-901 Leiria, Portugal*

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## Abstract

Roundabouts are widely accepted for their safety, capacity and environmental advantages. Although it can be easily recognized that the driver behavior is mostly related with the roundabout geometry.
This paper presents a detailed characterization of the driver behavior while crossing three consecutive double-lane roundabouts in an arterial road.
Driver behavior was described in three main levels: i) speed profiles; ii) lateral acceleration profiles; iii) roundabout geometry. It is shown that roundabouts can substantially reduce speed in the negotiation zone. The entry speed and influence zone depends on the desired speed in the upstream sections and on the roundabout geometric characteristics.

Selection and peer-review under responsibility of the Scientific Committee of EWGT2014

*Keywords:* Roundabout;  driver behavior; speed profile, influence zone, lateral acceleration profile.

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## 1. Introduction

Roundabouts are gaining wide acceptance as a viable alternative to traditional intersections around the world, but particularly in Europe and in North America. There are several studies reporting an increase of service levels and traffic flow when converting traditional intersections into roundabouts (Kimber, 1980; Louah, 1984; Stuwe, 1992;

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* Corresponding author. Tel.: +351 239 797 103
*E-mail address:* abastos@dec.uc.pt

Selection and peer-review under responsibility of the Scientific Committee of EWGT2014
doi:10.1016/j.trpro.2014.10.093

Akcelik et al., 1996). Increasing safety levels have also been mentioned in studies comparing before and after conditions (Flannery and Datta, 1996; FHWA, 2000; Persaud et al., 2001; Jensen and ApS, 2013), and in historical analysis studies (Gross et al., 2013). Therefore, roundabouts are increasingly proposed as an alternative method of managing conflict points in intersections (NHCRP, 2010).

It is widely accepted that the roundabout geometry influences the driver behavior and consequently his global performance (Bastos Silva and Seco, 2005). In fact, speed reduction is a benefit of a well-designed roundabout that usually results in homogeneous behaviors (Turner and Roozenburg, 2009).

However, when roundabout offer multiple circulation lanes, even with additional short lanes, providing higher capacities (Lindenmann, 2006), their speed and driver behavior control is less efficient (Bastos Silva, 2004; St-Aubin et al., 2013). The increase in the number of lanes allows drivers to have greater freedom in their behavior resulting in an increase of potential conflicts (Bastos Silva et al., 2006). An insufficient deflection of movements can also lead to a deficient speed control at the entry of the roundabout (Bastos Silva and Seco, 2005) and, consequently, to higher accident rates. These results increase the need for a detailed knowledge of drivers' behavior based on real observations as well as the main cause-effect relations between the geometric characteristics and the drivers' behavior.

Roundabouts have been studied since the 60's, mostly sponsored by Transport and Road Research Laboratory – TRRL (Brown, 1995). The experimental work requires high human and economic resources (Violette and Cardon, 1992; Bastos Silva, 2004), and because of that only a few studies were conducted. Nowadays, technological evolution allows extensive data collection in a systematic and highly accurate way, thus opening new research perspectives. Therefore, this work aims to assess at the evaluation of driver behavior when crossing roundabouts, with a detailed analysis before, during and after the roundabout crossing.

## 2. Methodological Approach and Site Characterization

In Portugal, the use of roundabouts with double-lane circulatory rings has become more frequent, namely in arterial roads. For this research a road stretch with 3.6 km was chosen comprising five consecutive double-lane roundabouts, three of them used by drivers in the through movement and two others only used to U-turn maneuvers. The analysis focuses only the through movement because it is the movement with high driver degree of freedom namely when compared to the turn left and right movements, and the one where the deflection level's influence is more important to the speed control. This road stretch is one of the most important arterial routes in the city of Coimbra, Portugal. The distance between two consecutive roundabouts, measured between the exit and the entry sections of two consecutive roundabouts, varies between 400 and 470 m which allow vehicles to stabilize their speed after crossing one roundabout and before starting decelerating to the other. The selected stretch has grades below 2% and a legal speed limit of 50 km/h, which is often exceeded.

Economics constraints justified the little sample of drivers adopted. An homogeneous sample of five different drivers (two females and three males), with more than 20 years of driving experience and ages ranging between 40 and 55, were invited to drive along the same circuit and to do multiple laps. All the drivers were advised to use alternatively the left and right entry lanes and then to follow the correct path along the roundabout's crossings, that is, respecting the lane markings.

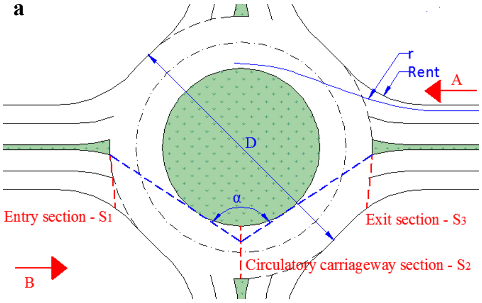
The work focused on the two-way through movements in roundabouts 1, 2 and 3 (see Fig. 1), leading to six case studies (1-A, 1-B, 2-A, 2-B, 3-A and 3-B). Each driver completed five laps under free flow conditions (with low traffic levels, allowing drivers to select their speeds with no conditioning by other drivers, and without having to yield at the entrance of the roundabouts), and no longer than 30 consecutive minutes to minimize any fatigue or habituation related constraints.

Fig. 1. Circuit adopted for the data collection

The three selected roundabouts have different geometrical characteristics but, because they are in the same arterial road, they have similar global dimensions (similar values for the inscribed circle diameter, *D*) –Fig. 2. It is also important to refer that two of the studied roundabouts are decentered, which leads to different deflection levels for each entry (represented by *α* and curvature degree – *c=1/r* – parameters). Based on this, different behaviors were expected in the approach zone of each entry studied.

The driver behavior profile was characterized based on the following variables: influence zone (length of the road, from upstream to downstream, in which the drivers' speeds are affected by the roundabout), speed and lateral acceleration profiles along the different cases studies. The speed variable, measured before, during and after each roundabout crossing, illustrates the roundabout as a speed control instrument. Finally, the lateral acceleration variable represents the acceptable discomfort level for each driver. For each intersection, the work was focused on the analysis of the different variables quantified in relevant sections of the roundabout ($S_1$, $S_2$ and $S_3$) – Fig. 2.

**a**



**b**

| Roundabout | Direction | *D* (m) | *α* (°) | $R_{ent}$ (m) | $c=1/r$ ($m^{-1}$) |
|---|---|---|---|---|---|
| 1 | A | 64 | 155 | 45 | 0.000054 |
| | B | 64 | 104 | 21 | 0.000772 |
| 2 | A | 55 | 117 | 23 | 0.000149 |
| | B | 55 | 115 | 15 | 0.00178 |
| 3 | A | 59 | 103 | 33 | 0.000132 |
| | B | 59 | 155 | 33 | 0.000045 |

Fig. 2. (a) Relevant sections to collect data; (b) Geometric characteristics of the roundabouts.

To support the research field data was collected using an instrumented vehicle. The vehicle is an 8-year-old Volkswagen Golf 1.9 TDi equipped with a datalogger device from Race Technology Ltd (DL1 MK3) – Fig. 3.

The data logger has a 6g 3-axis accelerometer and a 20Hz GPS that allows data to be referenced by time and position on the road. Positional accuracy is about 3 m – circular error probability – and the speed accuracy is better than 0.1 km/h. In addition to position, speed and accelerations, the data logger has several input doors that allow the connection to external sensors or even a connection to the vehicle's ECU to log engine data.

The data analysis was made using Race Technology's software which, with a maximum frequency of 20 Hz, allows the creation of global databases and/or to see isolated or combined kinematic variables. Fig. 3-c shows an example of the data output information using Race Technology's software with speed and lateral acceleration profiles of four different laps from the same driver. These images clearly show the evolution of each selected variable, providing an essential contribution for the database interpretation.

Fig. 3. Data collection: (a) Instrumented vehicle; (b) Data logger DL1 MK3 equipment; (c) Race Technology software – data output.

## 3. Results Analysis

This section intends to characterize the drivers' behavior during the through movement in a double lane roundabout of an arterial urban road. The database comprises a sample of 180 cases, and a balanced representation of trajectories that use both left and right entry lanes in different laps.

### *3.1. Influence zone*

The global influence zone is the length of road stretches before and after the roundabout where the adopted speed has a lower value compared to the speed away from the roundabouts (Fig. 4).

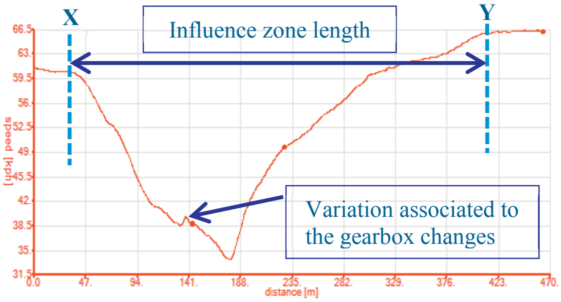
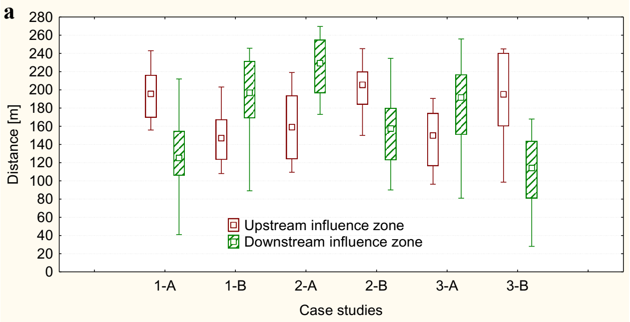


Fig. 4. Influence zone length.

The X point represents the section upstream the roundabout where the speed starts to decrease, ignoring some variations associated to gearbox changes. The Y point indicates the downstream section where the desired free flow speed is achieved and tends to stabilize.

The influence zones, upstream and downstream the roundabout, were identified for each trajectory of the six case studies. Fig. 5 shows the length of the influence zones for each roundabout and for each direction, as well as the mean approach speed.



**b**

| Case studies | Approach speed *(km/h)* | | |
|---|---|---|---|
| | Average speed | $P_{15}$ | $P_{85}$ |
| 1-A | 70.9 | 64.6 | 76.5 |
| 1-B | 68.3 | 61.3 | 74.8 |
| 2-A | 64.5 | 58.3 | 71.5 |
| 2-B | 71.8 | 66.9 | 74.8 |
| 3-A | 62.7 | 57.5 | 67.5 |
| 3-B | 66.3 | 60.2 | 71.4 |

Fig. 5. (a) Influence zone length before and after the roundabout; (b) Approach speed statistic parameters.

Data analysis shows a significant variation in the influence zone's length. Generally, for each roundabout, the upstream mean values are very different from the downstream values, regardless of the analyzed lap. However, the average values of the upstream and downstream influence length for the global sample are very similar and close to 170 m, in spite of having very high dispersion levels.

Also remarkable is the existence of roundabouts where the influence length is bigger before the roundabout and, in other cases, after the roundabout, although the distances between roundabouts are similar. In fact, in entries 1-A, 2-B and 3-B the length of the upstream influence zone is higher than the downstream length, indicating a possible correlation between these variables and the deflection level.

It is also noticeable that median values associated to each entry are similar to the correspondent exit in the opposite way (for example, the entry 1-A and the exit 1-B), indicating possible correlations among this variable and the length between consecutive roundabouts or among the corresponding desired speeds.

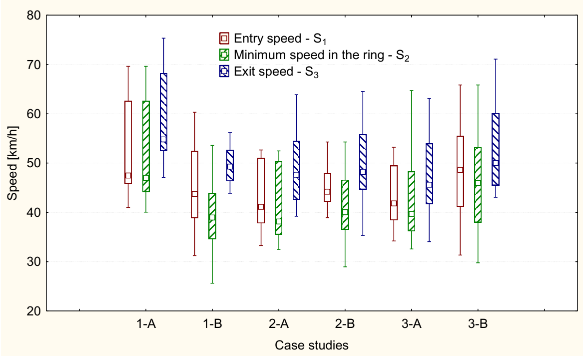
The high dispersion levels, normally more noticeable in the exit zone, could indicate different driving patterns between drivers, particularly in terms of the acceleration rate.

In their study, Violette and Cardon (1992) mentioned that drivers take their foot off the accelerator before the roundabout sign appears, with a distance between 400 and 500 m before the roundabout entry. They also referred that the acceleration phase after the crossing happens along 300 to 500 m which leads to an influence zone with a global length between 600 and 1000 m. These results are significantly above to those obtained in the present study. This difference was expected, because the road environments for the two studies are different. Violette and Cardon based their study in a peri-urban and rural environments, where the approach speeds are usually higher.

In order to test the roundabout as a speed control measure, the speeds were collected in five distinct sections for each roundabout: beginning of the influence zone (upstream of the roundabout), entry ($S_1$), roundabout's ring – where the speed is the lowest – ($S_2$), exit ($S_3$), and at the end of the influence zone (downstream of the roundabout). Fig. 6 depicts the general speed results for these sections on each case study.

The results show some variation in the average speed for each case study and section under study. Generally, the average speed is about 45 km/h at the entry and 50 km/h at the exit. The values shown in Fig. 6 are close to the reference values for double-lane roundabouts in rural areas (FHWA, 2000) and higher than the reference values for urban areas. It is also relevant to notice the same relationship between speeds in every roundabout, with a minimum speed in the ring zone and a maximum speed at the exit.

The results showed a possible correlation between the speeds in sections S1, S2 and S3, the influence zone's length and the approach speed. Apparently, the cross analysis of Fig. 5 and Fig. 6 shows that when the exit speed is higher, the length of the downstream influence zone tends to be lower. It is also important to refer that the roundabout acts as a traffic calming measure. Although the speeds vary in different roundabouts, it is possible to observe an average speed reduction of between 26 and 37% at the roundabouts entry while comparing to the approach speed.



| *ID* | *Entry speed – $S_1$ (km/h)* | | *Minimum speed in the ring – $S_2$ (km/h)* | | *Exit speed – $S_3$ (km/h)* | |
|---|---|---|---|---|---|---|
| | Average speed | σ | Average speed | σ | Average speed | σ |
| 1-A | 50.41 | 7.75 | 49.98 | 7.82 | 57.38 | 7.29 |
| 1-B | 44.86 | 7.08 | 39.57 | 6.52 | 49.42 | 2.92 |
| 2-A | 41.96 | 5.09 | 39.92 | 5.46 | 48.15 | 6.04 |
| 2-B | 45.08 | 3.88 | 41.26 | 5.94 | 50.15 | 6.66 |
| 3-A | 42.55 | 4.72 | 40.98 | 6.51 | 46.98 | 5.93 |
| 3-B | 49.06 | 7.87 | 47.44 | 8.37 | 52.68 | 7.52 |
| **Average** | **45.65** | **6.07** | **43.19** | **6.77** | **50.79** | **6.06** |

Fig. 6. Speed results for each case study and section S1, S2 and S3.

Regarding the length of the influence zone, the speeds collected in each section have a high dispersion even in the roundabouts rings. This fact calls into question the double-lane roundabout's ability to fully control drivers' behavior and, consequently, its capacity to enforce an homogeneous behavior. As a consequence, it is important to understand if the dispersion is related to: (i) the adoption of different strategies between the different drivers (inter-driver variation) or the natural driver inconsistency (intra-driver variation); (ii) the adoption of different behavior depending on whether the driver takes the right or the left lane at the entry and, consequently, during the roundabout's crossing.

For the first question, an analysis of variance (ANOVA) was applied to the collected speeds in the three most important sections of the roundabouts – S1, S2 and S3 (Table 1). The results showed a particular relevance in the inter-driver variation (F-statistics near 40 and p-value=0.0000). This result shows a tendency for a consistent intra driver behavior, with the speeds variability being essentially explained by the inter drivers behavior differences. This result shows a tendency for a consistent intra driver behavior, with the speeds variability being essentially explained by the inter drivers behavior differences.

Table 1. ANOVA and t-student test analysis.

| | | Entry speed ($S_1$) | Minimum speed in the ring ($S_2$) | Exit speed ($S_3$) |
|---|---|---|---|---|
| ANOVA | SS Driver | 4102.2 | 5473.8 | 4128.3 |
| | SS Error | 4388.2 | 5435.5 | 4732.8 |
| | Degrees of freedom | 4 | 4 | 4 |
| | Degree of Freedom | 175 | 175 | 175 |
| | MS Driver | 1025.5 | 1368.4 | 1032.1 |
| | MS Error | 25.1 | 31.1 | 27.0 |
| | F-statistic | 40.90 | 44.06 | 38.16 |
| | p-value | 0.0000 | 0.0000 | 0.0000 |
| T-student test | Average for the right lane | 44.2833 | 42.4474 | 49.6383 |
| | Average for the left lane | 46.5516 | 43.5424 | 51.6136 |
| | σ for right lane | 5.9387 | 7.1138 | 6.4425 |
| | σ for left lane | 7.4922 | 8.3699 | 7.4277 |
| | t-value | -2.2288 | -0.9385 | -1.8926 |
| | p-value | 0.0271 | 0.3492 | 0.0600 |

The ANOVA analysis was also individually used for each case study concluding that, usually, the individual results follow the same general trend.

The effect of the chosen entry lane (left or right) on the variance of speed values was tested using a t-student test (Table 1). The results show that the differences between the average values of the collected data are only statistically significant for the entry speed (p-value<0.05). The same analysis was individually applied for each case study sample, with only two case studies (1-B and 3-A) showing a significant difference for the entry, exit and downstream speeds. Based on these results, the analysis was continued without taking into account the lane choice.

### *3.2. Lateral acceleration*

Some variables were established in order to evaluate the discomfort level accepted by each driver to cross the roundabout. Usually, the discomfort is strongly related with the lateral acceleration variation (Violette and Cardon, 1990 and Bastos Silva, 2004). To simplify the analysis, this work assumes two indicators to represent the discomfort: (i) “lateral acceleration at the entry” representing the difference between the maximum lateral acceleration collected immediately before the entry section and the maximum value achieved in the roundabout’s ring; (ii) “lateral acceleration at the exit” representing the difference between this last value and the maximum lateral acceleration immediately after the roundabout exit. These two variables tend to represent the cumulative discomfort related with the curve and counter-curve at the roundabout’s entry and exit zones. Fig. 7 shows some statistic parameters for the maximum acceleration in the three sections (S1, S2 and S3) and for each case study (g=9.8 m/s2).

**a**

| Case studies | Maximum lateral acceleration in the ring *(g)* | | | |
|---|---|---|---|---|
| | Average | $P_{15}$ | $P_{85}$ | Máx. |
| 1-A | 0.43 | 0.38 | 0.47 | 0.50 |
| 1-B | 0.52 | 0.46 | 0.61 | 0.64 |
| 2-A | 0.57 | 0.50 | 0.62 | 0.66 |
| 2-B | 0.53 | 0.50 | 0.64 | 0.71 |
| 3-A | 0.60 | 0.53 | 0.68 | 0.72 |
| 3-B | 0.44 | 0.37 | 0.50 | 0.56 |
| **Global** | **0.52** | **0.42** | **0.62** | **0.72** |

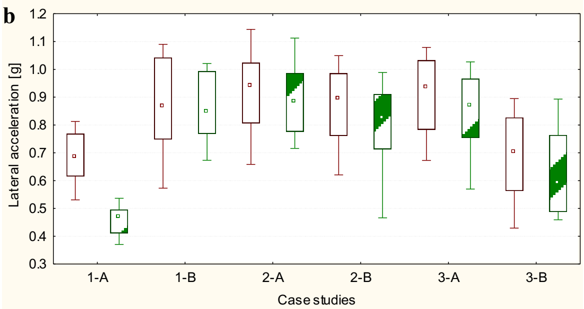


Fig. 7. Lateral acceleration for each case study: (a) maximum at the ring; (b) at the entry and exit zones.

The ANOVA analysis for this variable proved once again the importance of the intra-driver variation (p-value=0.0000; F =18.89 for lateral acceleration before the roundabout) while compared to the inter-driver variation. The results show only a few differences between the adopted accelerations in the two entry lanes, leading to the implementation of an aggregated data analysis. With the exception of circuits 1-A and 3-B, the values tend to be similar, although they are associated to high dispersion levels. The average of the amplitude values in the entry zone is about 0.83g, which means a high discomfort accepted by drivers during the roundabout crossings. It is noticeable that there is a higher discomfort level at the entry than at the exit zone, despite the higher exit speed. This result could indicate an abrupt turn of the steering wheel at the entry zone when compared to the exit zone, which could be directly related to the usually recommended implementation of higher curvature radius at the exits than at the entries.

A behavior analysis, based on experimental databases collected with instrumented vehicles, developed by Violette and Dupré (1990), concluded that in situations of difficult perception– non-critical driving situation – lateral accelerations would have average values under 0.51g. AASHTO (2001) also recommends, for comfortable operation conditions, a 0.3g value, although they admit that in normal situations this value can get to 0.9g and in extreme conditions 1.3g. The same publication refers that in road intersections there is an increase to values between 0.75g and 1.2g. Thus, the collected values presented in Fig.7-a are in accordance with the literature reference values.

## 4. Influence of kinematic/behavioral and geometric variables – single/multiple regressions analysis

After the previous data analysis, the relationship between different variables was evaluated. Despite of the small sample and low geometric variability, it seems relevant to evaluate the influence of kinematic/behavioral variables (approach speed, minimum speed, exit speed, lateral acceleration, etc.) and geometric variables ($R_{ent}$, $\alpha$, $c$ and $D$) in the entry speed and in the length of the upstream influence zone. In this task single and multiple regression techniques were applied.

A first approach tested the correlation between the length of the upstream influence zone and the approach speed, confirming a positive correlation ($R^2$=0.1477; p-value=0.0000) and proving that, when their speed is higher, drivers tend to take their foot off the gas pedal earlier. For the entry speed an analysis was also conducted relating this variable with some specific kinematic and geometric variables: approach speed, speed in the ring and curvature degree (c=1/r) – Fig. 8.

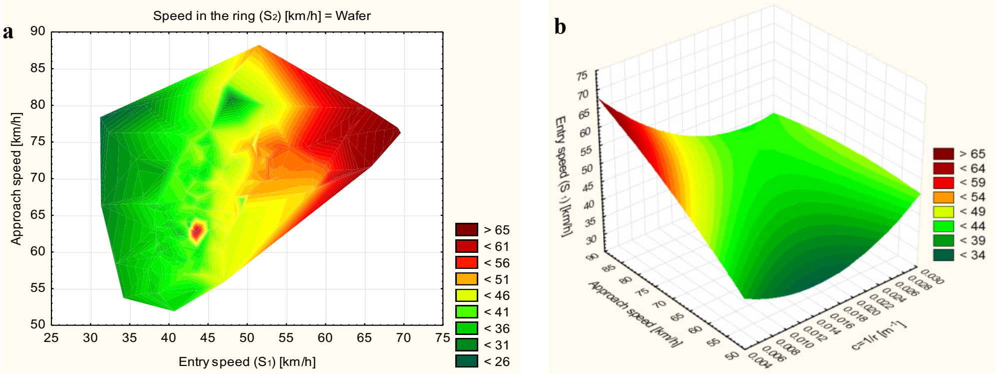


Fig. 8. Correlation between approach speed, entry speed ($S_1$) and: (a) minimum speed in the ring; (b) curvature degree, $c=1/r$.

As expected, a positive correlation was identified between the entry and the approach speeds, as well as the speed in the ring (Fig.8-a). It was also evident that the behavior observed at the entry usually determines the drivers' behavior during the crossing and at the exit of the roundabout with a significant and positive correlation between the three speed values (speed in S1, S2 and S3 sections). These results are consistent with the ones obtained by Bastos Silva (2004), where the relationship between these three variables was very explicit. A correlation between the approach and entry speeds with the curvature degree, 1/r (Fig.8-b) was also identified. In fact, Fig.8 shows a clear positive and almost linear correlation between the approach and the entry speeds and, at the same time, a negative and non-linear influence between the entry speed and the curvature degree.

These types of correlation were tested afterwards using multiple regression techniques. The length of the upstream influence zone and the entry speed were considered as dependent variables and the kinematic and geometric were considered as explanatory variables. Table 2 shows which of the independent variables are statistically significant of these two variables under analysis.

The approach speed was identified as an important explanatory variable for the length of the upstream influence zone, representing the sole kinematic/behavioral explanatory variable. For the geometric variables, the model chose the following ones: $R_{ent}$, curvature degree ($1/r$), $D$ and $\alpha$ angle. The correlation level ($R^2$) was 0.4716.

It is curious to find that a higher entry radius corresponds to shorter upstream influence zone (because it allows higher entry speeds) and the increase of the roundabout's dimension ($D$) corresponds to a higher length of the influence zone. It is possible to conclude that drivers react faster in the presence of larger roundabouts.

It is important to identify the high correlation level between the $\alpha$ angle and the curvature degree because both represent deflection parameters. This correlation was particularly noticeable in the modeling process since these variables were an alternative to explain the dependent variables without a significant loss of the variance levels.

By this time, the modeling process of the entry speed identified almost the same explanatory variables as statistically significant. The lateral acceleration at the entry, approach speed and curvature degree ($1/r$ and $1/r^2$) were identified and a higher correlation level was achieved ($R^2$=0.5603).

As expected in the first analysis (Fig.8), the approach speed contributes considerably to explain the entry speed values, as well as the curvature degree (as a variable representative of the deflection level). Also obvious is the contribution of the lateral acceleration to explain the entry speed values, which are strongly related to the curvature level. The entry speed tends to be higher when the driver assumes a higher discomfort level (lateral acceleration variations). For the roundabout geometric characteristics, the variables associated to the entry zone assume a higher importance in the entry speed control.

Table 2. Multiple regression analysis – explanatory variables for the upstream influence zone length and for the entry speed.

| | **Upstream influence zone length – $R^2$= 0.4716** | | | | **Entry speed – $R^2$= 0.5603** | | | |
|---|---|---|---|---|---|---|---|---|
| **Variable** | ***b*** | ***Std. Error*** | ***t*** | ***p-value*** | ***b*** | ***Std. Error*** | ***t*** | ***p-value*** |
| Intercept | -523 | 117.28 | -4.45683 | 0.000015 | 26.42 | 4.426 | 5.96861 | 0.000000 |
| Approach speed | 1.00 | 0.34 | 3.04968 | 0.002649 | 0.42 | 0.053 | 7.94857 | 0.000000 |
| *Rent* | -6.00 | 1.02 | -5.64805 | 0.000000 | Not significant | | | |
| Lateral acceleration in the entry | Not significant | | | | 46.98 | 5.322 | 8.82791 | 0.000000 |
| $1/r^2$ | -219368 | 41880.13 | -5.23801 | 0.000000 | 77296.63 | 9038.665 | 8.55177 | 0.000000 |
| $c=1/r$ | Not significant | | | | -3109.46 | 332.068 | -9.36392 | 0.000000 |
| *D* | 13.00 | 2.88 | 4.56848 | 0.000009 | Not significant | | | |
| $\alpha$ | 0.00 | 0.16 | 2.96148 | 0.003489 | Not significant | | | |

The developed regression analyses aim to understand and justify the type of relationship between the different independent variables, and do not necessarily explain the observed variability in the dependent variables. It is also important to take into account the limited size of the sample, particularly in terms of the roundabouts' geometric variability. By this fact, the geometric variability effect in the upstream influence zone length and the entry speed values should be taken with precaution.

## 5. Conclusions and future work

This paper focuses on the driver behavior in through movements on a set of double-lane roundabouts, located in an arterial urban road and under free flow conditions. In spite of the stretch under analysis being under a legal maximum speed limit of 50 km/h, approach speeds of 70 km/h were observed. It was confirmed that roundabouts are efficient traffic calming measures, able to significantly reduce the entry speed when compared to the upstream speed. Speed reductions between 26% and 37% were measured and the average entry speed was about 45 km/h. However, their ability to enforce homogenous driver behaviors wasn't so clear. This could be due to the fact that we are dealing with double-lane roundabouts, which gives a higher freedom of movement to the drivers.

The experimental results on the six case studies provided practical experience on interpreting speed profiles and illustrated significant intra-driver behavior variability, even while crossing a limited number of sites, confirmed by an ANOVA analysis.

The total length of the roundabout influence zone is between 400 and 500 meters. However, the regression analysis shows that this variable depends on the approach speed and on the deflection level of the roundabout (represented in this paper by the $\alpha$ angle, the curvature degree, the entry radius and the inscribed circle diameter).

Regarding the speed profiles, it was verified that the entry speed is strongly related to the approach speed. These relations were confirmed by the application of correlation techniques, which identified the approach speed, the lateral acceleration variation, and the curvature degree as statistically significant.

For future work, it seems important to study a larger sample of sites and a wider range of drivers, in order to investigate carefully the influence of geometry variation over driver behavior. Other future task should be to include the shortest path trajectories in the analysis which, by having intrinsically higher speeds in the three sections under analysis ($S_1$, $S_2$ and $S_3$), might provide another perspective for the performance assessment of roundabouts.

## Acknowledgements

This work was supported by FEDER funds through the "Programa Operacional Factores de Competitividade" – COMPETE and by national funds through FCT – "Fundação para a Ciência e Tecnologia" in the scope of the R&D project PTDC/SEN-TRA/122114/2010, *AROUND – Improving Capacity and Emission Models of Roundabouts* and by the *Energy and Mobility for Sustainable Regions – EMSURE* – Project (CENTRO-07-0224-FEDER-002004).

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