Characterization of Trajectories Adopted at Roundabout Crossings

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ABSTRACT
Multilane roundabouts normally result in somewhat large solutions that provide drivers with significant movement freedom which can sometimes lead to the adoption of incorrect trajectories by the partial or total invasion of adjacent lanes. This type of behavior tends to create a significant number of conflicting situations that although in general do not result in severe accidents, can however generate damage accidents with the consequent time delays and level of service drops.
This work aims to contribute for a better understanding of drivers’ behavior at roundabouts and is focused on the analysis of real trajectories of crossing movements in double lane carriageways.
The data collection process and trajectory reconstruction is also presented.
The analyses presented are based on a real data base with 2100 roundabout free flow crossing trajectories gathered by an instrumented vehicle in 20 different circuits using a group of 14 drivers.

KEY WORDS: Roundabout; driver behavior; real trajectories on roundabouts

1. INTRODUCTION AND STUDY GOALS
The use of roundabouts in urban and rural areas is normally associated with low emissions and accident levels as well as good levels of service. It is also highly adaptable to demand variations. This kind of performance has justified their adoption in many countries in conflict management in new intersections and also in upgrading existing intersections.
However the international experience has also shown that the performance level of a roundabout is highly dependent on its general characteristics and in particular in its ability to adequately influence driver behavior. In fact although a roundabout (when correctly designed) is an efficient physical speed control measure that result in homogeneous behaviors some functioning problems subsist related with driver behavior that become worse in severity and frequency when the entrance design is less restrictive and more entry and circulation lanes

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are provided. Generally roundabouts that offer multiple circulation lanes are associated with lower performance levels in terms of driver behavior control when compared with single lane roundabouts. The increase in the number of lanes allows drivers to have greater liberty in their behavior which as a result generates more conflicts.

The results here presented are based in recently developed research work (Bastos Silva, 2004), and intends to improve the knowledge of driver behavior on a roundabout namely on the trajectories adopted by drivers. The results are based on observations carried out on a wide range of circuits using an instrumented vehicle to record the trajectories adopted by the different drivers during the approach, crossing and exiting of roundabouts.

In the current paper one starts by explaining the data collection methodology as is the graphic and mathematical representation and characterization of drivers trajectories using a set of dispersion indicators measured in critical sections of the circuit. Finally the basic factors that influence each driver behavior and the way in which they are valued them is explored.

2. METHODOLOGY

The characterization of driver behavior based on the adopted trajectories was based on a direct observation of the trajectories described by a set of drivers, in the quantification of incorrect trajectories and on the medium values and dispersion registered in selected critical sections of the circuit. The critical sections were defined as the ones that tended to have the widest behavioral dispersions while at the same time would give a reasonable representation of the continuous driver behavior.

Three relevant sections were considered (Figure 1):

- Section $S_{ent}$ – entry section (at the give way line);
- Section $S_{circ}$ – located at the middle of the circulatory carriageway;
- Section $S_{exit}$ – at the roundabout exit;
In compliment and due to the use of a set of drivers and pre established circuits the relative importance of each of these components is evaluated on the global data set observed. This evaluation was made by comparing the trajectories at critical sections using regression techniques and ANOVA variance.

3. DATA COLLECTION

3.1 – Equipment

The difficulties related with the quantitative description of driver behavior and its precision have led to the use of complex data collection instrumentation that could assure the collection of relevant behavioral information.

The use of vehicles provided with a GPS (Global Positioning System) is the most common process used to determine real time vehicle position and therefore driver’s trajectories. However this process even when complemented with an inertial system that can minimize errors caused by low GPS signal areas can limit the quality of the vehicles’ location information on some areas. This is usually the case in urban sites where buildings, trees, antennas and other obstacles can deteriorate the GPS signal lowering the number of visible satellites and therefore the position information can have errors of between 1 and 5 metres (PIRES DA COSTA ET. AL; 2002). This is crucial particularly when the transversal position of the vehicle on the carriageway is important as was in the present study.

For these reasons in this study driver trajectories were reconstructed using the transversal position of the vehicle on the carriageway registered on video images (Photo 1_a and b). For this purpose the instrumented vehicle had an image recording system with four mini cameras linked to a multiplexer and video recorder (Photo 2). The cameras were strategically positioned in the vehicle in order to identify the driver and get a general panoramic view around the vehicle. This enabled the selection of the trajectories achieved in free traffic conditions.
One of the cameras was installed on the outside of the vehicle under the right exterior rear view mirror (Photo 1_b) in order to precisely record the transversal position of the vehicle. The small size of the cameras as well as their discrete location assured that the vehicle could circulate unnoticed in traffic without changing other drivers’ natural behavior.

3.2 – Site and Driver Selection

The study was supported by a real data base with 2100 trajectories made in free flow conditions. The driver sample was composed of fourteen University students. The selection criteria were gender, age group and driving experience. All drivers were male with ages between 22 and 29 years, had a driving experience of at least 2 years and tended to make between 15000 and 30000 Km annually.

Data collection was carried out on 20 circuits integrated in 2x2 carriageways and ahead crossing circuits as this was considered to be the movement that gave
greater behavioral freedom in terms of speed and trajectories adopted by the drivers.

The selected circuits present a reasonable range of design characteristics falling within acceptable values according to internationally accepted roundabout design guidelines. The only exception to this rule was circuit 9 which doesn't assure the minimum deflection criteria and circuits 17 and 18 which presented poor entry deflection levels. On the other hand circuit 10 had a highly offset roundabout center island which induced high deflection levels.

All sites were in urban areas except circuits 17 and 18 which were located in a sub urban environment.

3.3 – Data Collection Procedures

In order to assist the video image viewing to get the transversal position of the vehicle's wheel distance to the carriageway delimitation small reference markings were painted in the pavement. These markings were 0.5m apart and numbered according to their distance to the sidewalk acting as part of transversal rulers (Photo 3)

Since they were small and inconspicuous they were unnoticed by drivers.

In each circuit 9 sections were selected and marked in the pavement representing the beginning and end of the circuit and also some relevant sections for trajectory reconstruction such as the middle of the roundabout circulatory carriageway and trajectory inflection sections.
4. DATA PROCESSING

Trajectory reconstruction was based on the transversal position readings of the reference wheel of the vehicle at each of the 9 sections defined along the vehicles’ paths.

The representation of the trajectories along the circuit was based on a process of transforming discrete data from the 9 relevant sections into a continuous function after calculating the rectangular coordinates of each point of the vehicles path in the 9 relevant sections. The methodology adopted in the trajectory reconstruction consisted in the definition of a reference point for each circuit and calculation of the defining equation of each reference section (Figure 2). The coordinates of the trajectory points were then calculated projecting the transversal measurement collected from the video image on the x and y axis.

![Figure 2 – Rectangular coordinate determination on the relevant sections](image)

After determining the coordinates it is possible to determine the approximate distance between sections assuming that a vehicle’s movement can be described using circular equations between the relevant sections. The inter sections distances were therefore deducted from the general equation of a circle passing through three points \((x_1,y_1), (x_2,y_2)\) and \((x_3,y_3)\).

The transformation of discreet data into a continuous function was achieved using mathematical interpolation based on nine pairs of known points using a spline curve based adjustment.
5. ANALYSIS OF ROUNDBOUBT CROSSING TRAJECTORIES

5.1 – Behavioral Types

During the roundabout approach and crossing phase each driver adopts a behavior that translates into a real trajectory. According to the partial or total compliance with local traffic rules the trajectory can be classified as correct or as inappropriate. Although Portuguese legislation hasn’t defined behavioral rules and procedures to be adopted by drivers when approaching and crossing these type of intersections it is considered as adopted by several countries namely the United Kingdom (DETR, 1999) and Australia (ATC; 1999) that go ahead movements can use any one of the entry lanes. It was also considered that passing is forbidden in roundabouts, which means that the driver should remain in the same lane during crossing and exiting the roundabout.

This study was based on the definition of three types of behavior that can be briefly described as follows (Figure 3):

- **MINIMUM EFFORT BEHAVIOR** – this type of behaviour originates the most linear trajectory and is only conditioned by physical elements ignoring road markings;

- **CORRECT BEHAVIOR** – this type of behavior respects road markings which means that the vehicle stays on the same lane along the crossing and exiting maneuver. As a particular sub type an *ideal correct* behavior was defined as the one that among the possible correct trajectories adopts the one that achieves the maximum comfort.

- **REAL BEHAVIOR** - corresponds to the behavior adopted by each driver which is analysed in this study.
5.2 Basic Characterization of Real Trajectories

The graphic representation of the real trajectories highlights some interesting results namely that drivers have different behaviors according to the lane they enter the roundabout.

A detailed analysis of the right lane entries shows that entry and exit zones have moderate dispersion values in relation to the ideal right trajectory. The biggest dispersion values were found in the contour zone were the real trajectories cover almost all the width of the circulatory carriageway being particularly incident in the space located between the ideal right trajectory (represented in green in Figure 4) and the maximum comfort trajectory (represented in red).

On the other hand left lane trajectories show higher dispersions on the entry and exit areas highlighting some situations where on the circulatory carriageway zone drivers chose to change lane and exit the roundabout using the right lane.

Figure 4– Real trajectories (vehicle center axis): real ideal and min. effort trajectories – circuit nº5

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The observation of the real trajectories along the crossing circuit points out that there is a significant amount of incorrect trajectories.

The variability of the real trajectories in the selected circuits and particularly the fact that the observed dispersion is mainly within the range between the ideal trajectory and the maximum comfort one leads to the assumption that the driver seeks for straight trajectories to minimize his effort while trying to maintain his lane. The search for “driving principals” underlying this type of behavior lead to the conclusion that trajectory selection is ruled by a compromise between the “temptation” to maximize the comfort on one hand and the “obligation” to respect road markings on the other one.

5.3 Basic Characterization of the Transversal Deviations of Trajectories

5.3.1 General Characterization

The transversal deviations represent the distance between the real and ideal trajectories measured at the vehicles axis in three critical sections: entry section ($D_{ent}$), roundabout carriageway section ($D_{circ}$) and exit section ($D_{exit}$) (Figure 5). In practical terms the recorded transversal deviations on a given section show the difference between each real trajectory and the ideal one which points out the magnitude of the tendency of the driver to choose more straight-line trajectories and consequently maximize its driving comfort.

The positive transversal deviations represent trajectories linked to higher levels of sinuosity compared to the ideal trajectory and therefore negative values represent more straight-line trajectories.

Table 1 presents the average deviations and the dispersions range in each critical section of each roundabout.

Its analysis in association with the graphical representation of the transversal deviations registered in the selected critical sections (Figure 5) segregated by lane and roundabout show once again that sections right lane crossing and left lane exit are the ones that have higher dispersions. It is also visible in Figure 5 that the tendency to maximize driving comfort is more pronounced in the right lane trajectories (crossing section) where the invasion of the adjacent lane in the circulatory carriageway is almost a standard practice. In this section there are a significant amount of deviations that correspond to a “full” invasion of the adjacent lane (deviations greater then 0.7 meters – half the width of the vehicle). In average terms it was considered that there is a generalized tendency of deliberate invasion of the left lane where the average deviation is -1,02 meters (about ¾ of the vehicles width).

As for the left lane the smallest average deviations values as well as dispersion levels are in the entry section. The average deviation on this section is +0,28
meters showing that in average terms the driver is more receptive to accept lower levels of comfort associated with the ideal trajectory. Among the trajectories that invade the right lane there are few situations that correspond to “full” invasions of adjacent lane (deviations greater than 0.7 meters – half of the vehicles width) with the majority of situations representing a small overlapping of the centre line.

On the left lane exit section the strategy to maximize driving comfort is not negligible. The average deviation is -0.35 meters representing a tendency to adopt a more linear trajectories comparing to the ideal one. However it is a section that shows high dispersion values which is due to two clearly distinguishable behavior types: maintaining or not the vehicle on the left lane. It is therefore expectable that the significant variation is originated by the different strategies adopted by drivers.

The analysis of the average deviations and their dispersion ranges highlights the existence of a big variability in the inter-circuit results pointing out that the variation of the geometric design characteristics play a major role on drivers’ behavior. It is however important to notice that the inter-driver variability can also be significant as is showed in the following paragraphs.

Figure 5- Transversal deviations by critical section and circulation lane

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Table 1 – Transversal Deviations – average values and dispersion indicators

<table>
<thead>
<tr>
<th>CIRCUIT</th>
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<th>EXIT SECTION</th>
<th>CROSSING SECTION</th>
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<td>LEFT LANE</td>
<td>RIGHT LANE</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Aver. min max 15th 85th</td>
<td>Aver. min max 15th 85th</td>
<td>Aver. min max 15th 85th</td>
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<td>-1.02 -4.50 1.40 -1.40 -0.60</td>
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<td>-1.02 -3.96 1.20 -1.04 0.34</td>
</tr>
</tbody>
</table>

5.3.2 – Inter-circuit and Inter-driver Components Relative Importance

The evaluation of the importance associated to the inter circuit and inter driver variability was based on ANOVA tests with one factor of the total desegregated set. Its application rejected the null hypothesis in relation to the effect of the *inter circuit* and *inter driver* components in each set of the three critical sections. This demonstrates that the group effect of each one of these two factors is statistically significant in explaining their respective transversal deviations. The fact that not all drivers made all the circuits is particularly relevant and made impracticable the definition of a sub set with acceptable dimension (without zeros in the matrix) that would allow the use of the ANOVA test with two factors for the evaluation of the significance and relative importance of the interaction of these two factors. Therefore the relative importance of the factors was evaluated with simple and multiple regression techniques using artificial binary variables representative of the different *circuits* and *drivers* involved. The results are in table 2 and, in general, they confirm the conclusions drawn by the application of the variance analysis tests. As can be noticed the *inter circuit* variation is the most important factor in justifying the observed variance in the entry and exit sections justifying respectively about 18 and 30% of the total variance.
On the other hand the inter driver variation presents itself as the most important effect in justifying the variation of deviations in the crossing section.

<table>
<thead>
<tr>
<th>SECTION</th>
<th>TOTAL VARIATION COMPONENTS</th>
<th>ANOVA</th>
<th>SIMPLE REGRESSION</th>
<th>MULTIPLE REGRESSION (increase in $r^2$ level)</th>
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<td>18</td>
<td>18</td>
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<tr>
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<td>19</td>
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<tr>
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<tr>
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<td></td>
<td>INTER_DRIVER</td>
<td>18</td>
<td>15</td>
<td>+15</td>
</tr>
</tbody>
</table>

5.3.3 – Relations Between Driver Behavior and the Roundabouts’ Geometry

In order to achieve a successful roundabout design it is important to use solutions that induce natural and instinctive behavior in accordance to driver expectations without resulting in conflicts with vehicles that may be using adjacent lanes.

In mind with the observed inter circuit dispersion the next step will be the search for eventual inter relations between the different solutions and their geometric characteristics that can lead to extreme behaviors.

Circuits 2 and 10 are those that originated higher levels of dispersion in the crossing zone and circuits 13 and 14 generated the biggest average values with values close to 2 meters. However a group of solutions is identified where the trajectories registered follow closely the ideal trajectory namely solutions 9 and 11.

In absolute terms circuit 10 was the one that registered higher levels of deviation (6.0 meters) which can be associated to the fact that the roundabout centre island was significantly offset and consequently imposing low comfort levels. On the other hand solution 9 is the one that registers lower deviations which can be explained by the deficient deflection of this solution (direct trajectories possible).

In the left lane trajectories it is equally noticeable some variability in the dispersion values according to the circuits. Solutions 1 and 3 are those that on average incentive more sinuous trajectories in relation to the ideal one and solutions 11 and 17 are the ones that induce drivers to exit the roundabout invading the right lane. There are also a significant number of solutions where the invasion tendency is not significant occurring only occasionally. Actually most
roundabouts have good results since the situations where there is a pronounced invasion of the adjacent lane are the minority and outside the inter percentile range of 15 and 85th.

Solutions 11, 13, 17 and 20 are exceptions with a high number of straight line trajectories in the 15 to 85 inter percentile range (see table 1). The analysis of the geometric characteristics of these solutions points out that all of them have high exit angles which in practical terms means that they impose high exit deflection levels.

These results must be further evaluated through a detailed analysis of the statistical inter relations between the observed deviations on the different sections and the main geometric characteristics which justifies further research on this subject.

5.4 - Real Trajectory Evaluation

The driving effort mitigation results sometimes in the search for trajectories that more or less tend to diminish the effect of movement deflection and therefore in the adoption of several deviations when compared with the ideal trajectory. This aspect supports the physical interpretation of the results previously presented converting the recorded deviation values in percentage of trajectories considered incorrect.

The results were quantified in percent terms and were focused on three indicators: trajectories that only overlap the center mark line (P_PE) and those that interfered with the adjacent lane in at least 0.7meters (P_0.7m) or 1.4m (P_1.4m) which is equivalent to respectively half the width and full width of the vehicle used in the data collection.

In global terms as stated before the tendency to minimize the driving effort reverts in straight line trajectories with the consequent invasion of the left lane by vehicles that enter the roundabout using the right lane. About 63% of the observed trajectories interfere with the adjacent lane and 30% represented an occupation of more than 0.7metres. The same effect is visible in the left lane trajectories when the driver opts to abandon the roundabout fully invading the right lane disrespecting the road markings indications. These trajectories represent approximately 40% of all observations.

Roundabout 17 is the one with more straight line crossing while roundabout 9 didn’t have any incorrect trajectory. Once again the imposed deflection levels can be assumed to be responsible for these types of behavior.

Among the left lane trajectories it is worth noticing that 100% of the trajectories overlap the center lane in roundabouts 17 and 18. Looking into the geometric
characteristics of these exits it is clear that both are wide and have high exit angles which possibly translates in a driver attempt to minimize his driving effort while letting space for other vehicles in the adjacent lane.

These results show that drivers are willing to assume some amount of discomfort imposed by movement deflection while crossing the roundabout. However, when the design imposes higher levels of discomfort then the ones the driver is willing to assume he will try to lower its effect by adopting more comfortable trajectories and consequently invading the adjacent lane.

On the other hand when analyzing inter_driver variation (Figures 8 and 9) the importance of this factor is confirmed. On the right lane drivers number 9 and 11 are the ones that seek straighter trajectories while on the opposite side driver 2 rarely overlaps road markings.
On the left lane and although there is a significant tendency to invade the right lane near the entry section it is less than half of the vehicles width in the majority of the observations with few cases above the vehicles width (P_1.4m). The exception is once again driver 9 that in 5% of his trajectories deliberately invades the adjacent lane. It is however clear a high behavioral inter driver variability which points out to the fact that each driver has a unique driving style.

Incorrect trajectories on the exit section are mostly due to the tendency shown by some drivers to abandon the roundabout carriageway through the right lane. Driver 11 and to a less extent drivers 1, 3, 7, 9 and 13 show out as those that try to minimize their driving efforts while on the other hand drivers 2, 8, 10 and 12 are the ones that are more respectful to road markings. It is once again noticeable that each driver has a distinct behavior.
6 - MAIN CONCLUSIONS

The observation of the real trajectories in roundabout crossings points out to a significant tendency of incorrect behaviors which are shown by overlapping the adjacent lane. This effect differs according to lane selected by the driver to enter the roundabout. The biggest levels of adjacent lane invasion were observed on the carriageway section when entering in the right lane and exit section when using the left lane.

The variability of the real trajectories in the selected circuits and the fact that mostly the dispersion registered in the critical sections is confined by the ideal and maximum comfort trajectories is consistent with the principal that driver behavior is ruled by the weighting of two fundamental criteria: the “obligation” to comply with road markings and the “temptation” to maximize driving comfort.

Most of the variability registered in the trajectories is due to either the inter-circuit variation and therefore to the main geometric characteristics of each design, or the driving style, with the inter-circuit variance being the most important component in explaining the observed trajectory variation in the roundabout carriageway zone.

Crossing these results with the main geometric characteristics highlights the importance of the deflection and the entry angle in controlling driving behavior. These results have in fact confirmed some of the expectable interrelations between the roundabouts’ geometric characteristics and the observed drivers’ behavior, but there still exists a need for a better understanding of the quantitative relations between them. Some extra work is thus needed do be done in this area.

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