A behavioural lane changing model for roundabout design

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Abstract

In recent years, intersections planned with roundabouts have had a remarkable diffusion, especially in urban areas. Compared to conventional intersections, this system is suitable to improve road safety. In Italy, in spite of many positive experiences that have been made, still there is no defined norm and regulation for roundabouts. This research can give guidelines for norms and roundabout design, through the development of a generalized behavioural model. In particular, the proposed model simulates user’s lane changing choices inside the roundabout.

In this paper, a behavioural Nested Logit model is proposed. Preliminary results, obtained through application on some urban roundabouts, showed that roundabouts perform depending not only on the flow in the weaving area and the length of the weaving area, but also on the speed of vehicles changing lanes and critical gaps.

The relationship between these quantities and intersection capacity can be traduced:
- under the same conditions of gap acceptance, changing lane probability increases proportionally to the speed difference between the vehicle that changes lane and the vehicle behind on the adjoining lane;
- with the same length of weaving area, the capacity of the intersection increases inversely proportional to flow on the weaving area.

Given our model it can be possible to plan the weaving areas imposing the intersection capacity and given flows on the weaving area. In other words, the dimensioning of the weaving areas is possible by knowing the O/D matrix.

Keywords: roundabout, behavioural model, lane changing.
1 Introduction

This paper originates from a research project conducted by the Department of Territorial Planning at the Calabria University of Studies that is focused on examining in detail all factors that may influence the functioning of roundabouts.

Roundabouts, compared to regular intersections (regulated by street codes or by traffic lights), guarantee more security because they have less conflict points, they do not have left turns, they present a better way of entering the intersection and, above all, the moving vehicles, while changing lanes, tend to move more slowly. For this reason, in Italy, there is a growing interest shown in recent years by companies managing the principal ways (urban and suburban) towards this kind of intersection.

Currently, the reference rules and guidelines that Italian technicians and designers use come from the United States, or other European countries such as France or Great Britain. This modus operandi presents some obstacles, since it is difficult to adapt design rules from a different country to Italy, given the vast differences in driving behaviours. It is within this context that the behavioural model for changing lanes in a roundabout was born, and is presented in this paper.

In the literature, numerous behavioural models of lane change have been presented in different contexts, for example, highways (weaving areas) [1, 2, 3] and freeways (intersections regulated by traffic laws and traffic lights) [4, 5]. Several studies have been conducted on the behavioural analysis of roundabout users through the use of cellular automata [6] which co-relate measurements (arrival rates, turning rates, roundabout topology) with the temporal distribution of the roundabout arrivals.

No behavioural lane changing models have been applied to roundabout’s design. The model proposed is a random utility model based on the hypothesis that every car driver is a rational decision–maker that tends to maximize the utility connected with his choices. In particular, the model is based on a tree-like structure simulating the different decisional steps that bring the user to execute lane changing.

At a superior decisional level, the lane change is evaluated based on the destination of the user. The user would enter the weaving area only if this is needed to reach is destination. The user can now decide to move to the right lane or to the left lane, and then change lane only if the available gap is acceptable. We can associate a utility equation for the generic user $n$ that at the time $t$ considers the hypothesis to change lane:

$$U_{t,n} = \gamma^t X_{t,n} + \nu_n + \epsilon_{t,n}$$  \hspace{1cm} (1)

where:

$\gamma = \text{vector of parameters to evaluate;}$

$X_{t,n} = \text{attributes vector;}$
\( \nu_n = \) random residual specific for user \( n \), independent from time;  
\( \varepsilon_{t,n} = \) random residual specific, dependent from time.

The hypothesis on random residuals is the following:
- random residuals \( \nu_n \) are independently distributed between two generic users \( n \) and \( n' \) with a variance \( \sigma^2_v \);
- random residuals \( \varepsilon_{t,n} \) are independently distributed between two generic users \( n \) and \( n' \) and/or between two generic instants \( t \) and \( t' \) with variance \( \sigma^2_e \);
- terms \( \nu_n \) and \( \varepsilon_{t,n} \) are independently distributed.

Those hypotheses implicate the covariance between \( U_{t,n} \) and \( U_{t',n'} \) which is equal to
- \( \sigma^2_v + \sigma^2_e \) if \( t = t' \) and \( n = n' \);
- \( \sigma^2_v \) if \( t \neq t' \) and \( n = n' \);
- 0 in any other case.

The parameters of this model can be calibrated using the Maximum Likelihood Method.

The proposed model has a general validity and can be applied to several urban roundabouts. In order to define and calibrate this model it is very important to pre-define traffic measures targeted specifically to predict vehicle trajectories. Nevertheless, the required parameters to validate this model are not easily acquired using traditional survey instruments. In this paper we present the results of analysis finalized to evaluate the drivers’ minimum accepted gap to perform a lane change in a roundabout. We specified tree-Logit models simulating the behaviour of a single user through a technique of image acquisition from a video. The attention was also finalized to specify and calibrate a model of lane change in a roundabout in ordinary traffic flow conditions.

2 Description of the model

The calibrated model takes some important cues from the behavioural models of lane change proposed by Ahmed et al [1], but it is different because of the specific applicative context. The study was produced under the following conditions:
- roundabout with 4 entry lanes;
- uninterrupted flow conditions;
- lane change from right to left and left to right.

With the above assumptions, the decision tree takes the following shape:

From the tree, it appears evident how the lane change happens if the driver decides to change and, evaluating the time gap available, or the time distance between the vehicle that leads and the vehicle that follows on the adjoining lane, he decides to change lane accepting the gap itself (event A = left lane change; event B = right lane change).
The change will not happen if any of the following events occurs:

- event C: the driver decides to change, but there is not an acceptable time gap;
- event D: the driver decides not to change lane.

The direct observation of the occurrence of events A and B allows us to define the probability that a vehicle would change lane, \( P(Y) \) as:

\[
P(Y) = P(A) + P(B),
\]

while the probability that a vehicle would not change lane is:

\[
P(N) = P(C) + P(D) = 1 - P(Y).
\]

Events Y and N can be derived from the vehicle’s trajectories.

It is assumed that the choice of the alternative is made using a Nested Logit model; elementary alternatives (final nodes of the tree) are identified together with each tree branch. Also, each branch is given a function, composed of a systematic part and an aleatory part. Tree branches coming out of each node are hypothesized independent from each other; alternatives belonging to the same group have a covariance different from zero; utilities are then distributed according to Weibull’s distribution. Because of these hypotheses, systematic utilities (\( V_i \)) associated to each branch I of the tree and the inclusive utilities (\( Y_j \)) associated to nodes j are:

\[
V_1 = \beta_{1i} \cdot x_1
\]

\[
V_2 = \beta_{2i} \cdot x_2
\]

\[
V_3 = \beta_{3i} \cdot x_3
\]

\[
V_4 = \beta_{4i} \cdot x_4
\]
\[
Y_1 = \ln \left[ \exp \left( \frac{V_1}{\theta_i} \right) + \exp \left( \frac{V_2}{\theta_i} \right) + \exp \left( \frac{V_3}{\theta_i} \right) \right] 
\]

(8)

\[
Y_0 = \ln \left[ \exp \left( \frac{V_4}{\theta_0} \right) + \exp \left( \frac{\theta_i \cdot Y_1}{\theta_0} \right) \right] 
\]

(9)

where:
\( \theta_i \) represents the generic parameter to calibrate associated to the node I of the chosen tree;
\( \beta_i \) represents the generic vector of parameters to calibrate associated to terminal branch I of the chosen tree;
\( x_i \) represents the generic vector of attributes associated to the branch I of the chosen tree.

Given the above, the probabilities of choosing one of the tree nodes are the following:

\[
P(A/NI) = \frac{\exp(V_A)}{\exp(\theta_i \cdot Y_1)} 
\]

(10)

\[
P(B/NI) = \frac{\exp(V_B)}{\exp(\theta_i \cdot Y_1)} 
\]

(11)

\[
P(C/NI) = \frac{\exp(V_C)}{\exp(\theta_i \cdot Y_1)} 
\]

(12)

\[
P(NI) = \frac{\exp(\theta_i \cdot Y_1)}{\exp(\theta_i \cdot Y_1) + \exp(V_D)} 
\]

(13)

\[
P(D) = \frac{\exp(V_D)}{\exp(Y_0)} 
\]

(14)

Hence, the probabilities of performing (or not performing) the lane change are:

\[
P(Y) = P(A) + P(B) = P(NI) \cdot P(A/NI) + P(NI) \cdot P(B/NI) 
\]

(15)

\[
P(N) = P(C) + P(D) = P(NI) \cdot P(C/NI) + P(D) 
\]

(16)
3 Data acquisition and model calibration

The proposed model was calibrated using a satisfactory number of trajectories of the vehicles moving inside the roundabout located in proximity of the highway entrance in Cosenza, Italy (fig. 2). The monitored roundabout is composed by 4 entry lanes and has an external diameter of about 75 meters. The trajectories of the vehicles were monitored for one hour with a camera positioned inside the roundabout (fig. 2), measuring a flow (Qs) of 1300 vehicles per hour.

Using Adobe Premiere 6 software, from the analysis of the video the attributes that characterize vehicle trajectories are estimated. In particular, we identified 430 trajectories. After the first study, the survey reconstructed 99 trajectories of lane change to the left, and 115 to the right. Once the vehicle which effectuated the lane change was identified, the trajectories of the preceding and following vehicles in the same lane, and in the adjoining lane were determined. We then estimated the following parameters:

- variable dummy (0/1) inherent to the vehicle entering the weaving area;
- instantaneous speed of vehicle n effectuating the change (V);
- instantaneous speed of vehicle n1 preceding n on the adjoining lane (V1);
- instantaneous speed of vehicle n2 following n on the adjoining lane (V1);
- time headway between vehicles n1 and n2;
- distance headway between vehicles n1 and n2.

Figure 2: Surveyed roundabout plan.
We then statistically analyzed the data to determine the distribution of accepted gaps. From the above data it emerged that gaps are distributed according to a Pearson type III curve and, in particular, the critical gap, corresponding to about 80th percentile, which is equal to 4.4 seconds.

Calibrations, measured with the maximum likelihood, offer comforting results, as shown in the table 1. From a first lecture of the indicators of global calibrations, a value of parameter $\rho^2$ equal to 0.74 was found.

The model highlights significance of the variables relative to the vehicles speed following the car that is moving on the adjoining lane, and the time headway between vehicles preceding and following. Parameters are correctly calibrated in the sign.

Table 1: Model calibration results.

<table>
<thead>
<tr>
<th>Utility</th>
<th>Attribute</th>
<th>Unit of measure</th>
<th>Parameter $\beta$</th>
<th>t-student</th>
</tr>
</thead>
<tbody>
<tr>
<td>V1</td>
<td>$\Delta t$</td>
<td>sec</td>
<td>$\beta_{\Delta t} = 1.147$</td>
<td>7.73</td>
</tr>
<tr>
<td>V1</td>
<td>V2L</td>
<td>Km/h</td>
<td>$\beta_V = -0.1653$</td>
<td>-4.59</td>
</tr>
<tr>
<td>V2</td>
<td>$\Delta t$</td>
<td>sec</td>
<td>$\beta_{\Delta t} = 1.147$</td>
<td>7.73</td>
</tr>
<tr>
<td>V2</td>
<td>V2R</td>
<td>Km/h</td>
<td>$\beta_V = -0.1653$</td>
<td>-4.59</td>
</tr>
<tr>
<td>V3</td>
<td>Const</td>
<td></td>
<td>$\beta_C = 0.7321$</td>
<td>5.96</td>
</tr>
<tr>
<td>V4</td>
<td>1</td>
<td></td>
<td>$\beta_D = -31.56$</td>
<td>-7.10</td>
</tr>
<tr>
<td>$\theta_1$</td>
<td></td>
<td></td>
<td></td>
<td>6.83</td>
</tr>
</tbody>
</table>

Test

<table>
<thead>
<tr>
<th></th>
<th>LogL(opt.)</th>
<th>LogL(0)</th>
<th>LR(0)</th>
<th>$\chi^2_{4\text{ d.o.f.}} = 9.49$</th>
<th>$\rho^2$</th>
<th>$\rho_{\text{bar}}^2$</th>
</tr>
</thead>
</table>

The analysis of the results provided by the model is simplified by the following illustration (fig. 3), in which the probability of changing lane for a generic driver in the weaving area of the roundabout is a function of the speed of the vehicles following on the adjoining lane as well as a function of the accepted gap.

From the given observations, the following fact emerged: the weight taken on by the speed $V_2$ is a function of the expression of utility and is the same in both lane-changing maneuvers (either left or right). Nevertheless, in the figure 3, given the analogy of the cases, only the characterizing values of the lane change to the left lane is diagrammed.

Analyzing the graphics, it is evident how the probability of executing the exchange in the roundabout is bigger when the available time headway is growing and the speed of the vehicle following in the adjoining lane is decreasing. Elaborating the data and creating the model we considered the value of the changing vehicle’s instantaneous speed, an average of 15.8 Km/h.
Figure 3: Relationship between P(Y), Δt and V2.

For time headway values over 12 seconds, the choice of lane change results being independent from the speed of vehicles following the changing car; for smaller values a strong variance of the probability for a lane change in relation to other variables present. It is observed, nevertheless, that for values of speed V2 (see precedent note) bigger or equal to speed V, the probability of a successful lane change is decreased of about 20% for time headway equal to 3 seconds.

4 Conclusions

The acquisitions of data relative to the changing lane vehicle’s trajectories in a roundabout allowed us to specify and calibrate a behavioural model relative to the lane change.

The vehicular circulation control, in order to improve mobility and security standards, can be achieved through behavioural models like the one proposed in this study.

The development of this research will be able to transfer the model characteristics of generality, for the application and contexts different from the one examined. The acquisition of more data relative to different roundabouts will allow us, in fact, to calibrate models generally valid and will be able to provide fundamental structure to blueprint choices for roundabout, optimizing geometries and increasing safety.

References


