Traffic conflicts at roundabouts: risk analysis under car-following conditions

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Abstract

Roundabouts have had a remarkable spread since the 80s of the twentieth century, especially in Europe. Compared to the conventional intersection’s layout, traffic control systems based on roundabouts are suitable for improving road safety and urban design. Nevertheless, much research has addressed investigating safety issues related to the traffic conflicts of interesting roundabouts’ traffic flows. The focus of this paper is on the analysis of safety levels at roundabouts as regards the rear-end vehicles’ interactions in car-following conditions. Levels of safety are evaluated on the basis of a traffic conflict technique applied to vehicles’ trajectories obtained experimentally from a frame-by-frame analysis of video-taped traffic data. In order to estimate traffic conflicts, reactions of following vehicles were observed at a roundabout case study, and then were compared to the estimated ones obtained from a car-following model, based on a properly calibrated stimulus-response function. Keywords: driver behaviour, roundabout, car-following, road safety.

1 Introduction

Intersections can be considered as the most sensible part of the road network due to the fact that intersection accidents constitute a significant portion of total crashes [1]. In many countries in the world, in order to increase road safety and capacity at the same time, many intersections have recently been converted into roundabouts. Roundabouts, indeed, eliminate or change the dynamics of conflict types, reducing crash severity and drivers’ speeds [2]. Therefore, more studies and research in this sector could provide additional information on the safety on roundabouts, and, consequently, suggest helpful solutions for planners and...
designers in identifying existing deficiencies and in refining their design concepts.

This paper presents a risk analysis at a roundabout with particular attention to rear-end interactions among vehicles. With the help of a video image processing technique and a frame-by-frame analysis, more than 500 trajectories were observed at a roundabout case study, determining the instantaneous speed and acceleration of vehicles. This trajectories’ sample allows the authors to calibrate a car-following model able to replicate rear-end interactions of the traffic stream. For each couple of vehicles (lead and following vehicle) a risk analysis was performed using traffic conflict technique [3–6]. In particular, for each couple of lead and following vehicles Deceleration Rate to Avoid the Crash (DRAC) was determined, identifying potential conflict scenarios. Finally, the authors compare the conflict scenarios derived from the direct observation of vehicles’ manoeuvres with those obtained applying a properly calibrated car-following model.

2 State of the art of car-following models

In car-following theory, the following vehicle (fv) decelerates or accelerates as a response of the stimulus induced by leading vehicle (lv). The different models vary according to the definition of the stimulus that, generally, may include the velocity and the acceleration of the lv, the relative velocity and spacing between lv and fv. Chandler et al. [7] formulated a first car-following model in which the stimulus is specified as the relative velocity between lv and fv. The functional form of the model is:

$$a_n(t) = \alpha \cdot \Delta V_{n,\text{front}}(t - \tau_n)$$

where,
\(\tau_n = \) perception time of driver n;
\(a_n(t) = \) acceleration applied by driver n at time t;
\(\Delta V_{n,\text{front}}(t - \tau_n) = \) speed difference between user n and the preceding vehicles in the same lane at time t-\(\tau_n\);
\(\alpha = \) sensitivity = constant.

On the basis of this first formulation, Gazis et al. [8], in 1959, suggested a model taking into account the relative spacing between two successive vehicles:

$$a_n(t) = \frac{\alpha}{\Delta X_n(t - \tau_n)} \cdot \Delta V_{n,\text{front}}(t - \tau_n)$$

where,
\(\Delta X_n(t - \tau_n) = \) relative spacing between lv and fv at time t-\(\tau_n\).

In 1960, Edie [9] modified the model considering that the velocity of vehicle itself influences driver behaviour. In consequence, the model can be more generally expressed as:

$$a_n(t) = \alpha \cdot \frac{V_n(t - \tau_n)^\beta}{\Delta X_n(t - \tau_n)^\gamma} \cdot \Delta V_{n,\text{front}}(t - \tau_n)$$
where,

\( V_n(t) \) speed of the driver \( n \) at time \( t - \tau_n \).

Many calibrations of the model were carried out from 1959 [10,11], using various approaches and on different scales (microscopic and macroscopic).

Therefore, the formulations defined by Chandler et al. [7] and by Gazis et al. [8] can be considered special cases derived from the above-mentioned model.

The recent developments in sensor technologies led to the definition of more general models and different combinations of \( \beta \) and \( \gamma \) [12–14].

In 1996, Subramanian [15] proposed a formulation based on the GMN model, in which a random term appears associated with the \( n \)-th user at time \( t \). This term is normal distributed while perception and reaction time \( \tau \) is considered as a random variable truncated lognormal distributed:

\[
a_n(t) = \alpha \frac{V_n(t - \tau_n)^\beta}{\Delta X_n(t - \tau_n)^\gamma} \cdot \Delta V_{n \text{front}}(t - \tau_n) + \varepsilon_n(t)
\]

In 1999, Ahmed [16] formulated a new expression of the GMN model, considering the effect of flow’s density \( (K_n(t - \varepsilon \tau_n)) \) in the sensitivity function and suggesting a non-linear relationship between acceleration and the stimulus function \( (\Delta V_{n \text{front}}(t - \varepsilon \tau_n)) \):

\[
a_n(t) = \alpha \frac{V_n(t - \varepsilon \tau_n)^\beta}{\Delta X_n(t - \varepsilon \tau_n)^\gamma} \cdot K_n(t - \varepsilon \tau_n)^\rho \cdot \Delta V_{n \text{front}}(t - \varepsilon \tau_n)^\lambda
\]

in which \( \varepsilon \) (\( \in (0;1) \)) is a parameter that describes the \( n \)-th user’s perception of the congestion level.

Besides the above-described models, based on the stimulus-response function, there are other types of car-following models, some of them based on the concept of braking distance [17–19], as well as models based on linear relations [20–23], psychophysical models [24–27], models based on fuzzy logic [28–31], and other models based on ITS systems [32–34].

### 3 Analysis of traffic conflicts under car-following conditions: case study

Traffic flow was analysed at a roundabout placed near the motorway turnoff of Cosenza, a medium-sized town in southern Italy, in order to calibrate the GMN car-following model revised by Subramanian [15], and evaluate the potential conflict scenarios for rear-end vehicles’ interactions.

#### 3.1 Data collection

The test area is close to the Cosenza North motorway turnoff, which is an important node in the local road network because of the presence, in the neighbourhood, of the Arcavacata University campus, the most important regional university complex. Considerable traffic flows use this roundabout,
because it is located along the only corridor that connects both the railway station and the highway with the university campus.

The geometric features of the intersection have been obtained by preliminary surveys: this is a single-lane roundabout (the inscribed circle diameter varies between 68 and 80 meters) with four entries.

Afterwards the roundabout was video-taped by a camera during the afternoon peak hour, between 1:00 pm and 2:00 pm.

This survey allowed us to obtain the O/D matrix during the peak hour, to individuate the busiest entries of the roundabout and to evaluate the traffic flow in the circulatory roadway (Figure 1).

![Figure 1: Traffic flows (veh/h) during peak hour.](image)

The car-following conditions occur for distances of less than 75 metres in accordance with the theory of Aycin and Benekolah [35]; indeed, for distances greater than this critical value, user behaviour is not influenced by preceding vehicles in the same lane.

The roundabout monitored was divided into further trunks in order to determine the most important parameters for the definition of the car-following model. The aim of this discretization is to carry out the instantaneous dynamic features of each vehicle.

The following data were extracted from the recording stage: $V_n(t)$, speed of the user $n$ ($fv$) at instant $t$; $V_n(t-\tau_n)$, speed of the user $n$ ($fv$) at instant $t-\tau_n$; $V_{n-1}(t-\tau_n)$, speed of the user’s predecessor ($fv$) at instant $t-\tau_n$. 
In order to determine the perception and reaction time ($\tau$) of the users, it was used an experimental relationship suggested by Italian rules [36], in which:

$$\tau_n = 2.8 - 0.01 \cdot V_n(t)$$  \hspace{1cm} (6)

The determination of the reaction (acceleration or deceleration) applied by the $n$-th user at instant $t$ was carried out using the following equation:

$$a_n(t) = \frac{V_n(t) - V_n(t - \tau)}{\tau}$$  \hspace{1cm} (7)

### 3.2 Data analysis and calibration of the model

The analysis of the trajectories recorded through the video-taping stage suggested that a higher percentage of the manoeuvres were carried out in deceleration conditions, hence the authors calibrated a general deceleration model in car-following conditions.

A statistical analysis was carried out to determine the correlation among the observed parameters useful to describe the car-following model.

The deceleration applied by the $n$-th user at instant $t$ proved to vary linearly both with velocity $V_n$ and with $\Delta V_n$, whereas the relationship between the same parameter ($a_n$) and the distance headway $\Delta X_n$ is better characterized by an exponential function (Equations (8), (9) and (10)).

$$a_n(t) = -2.004 + 0.062 \cdot V_n(t)$$ \hspace{1cm} (8)

$$a_n(t) = 0.026 + 0.065 \cdot \Delta V_n(t)$$ \hspace{1cm} (9)

$$a_n(t) = 1.436 \cdot \exp(-0.041 \cdot \Delta X(t))$$ \hspace{1cm} (10)

The parameters of the model ($\alpha$, $\beta$, $\gamma$) were estimated through the Nonlinear Least Square Analysis, whose numerical solution was provided by the damped least-squares (DLS) method, or Levenberg-Marquardt algorithm. The general expression of the model assumes the following shape:

$$a_n(t) = 0.001 \frac{V_n(t - \tau_n)^{4.98}}{\Delta X_n(t - \tau_n)^{0.48}} \cdot \Delta V_n^{front}(t - \tau_n) + \varepsilon_n(t)$$ \hspace{1cm} (11)

The calibration of the model shows that parameters $\alpha$, $\beta$ and $\gamma$ have order of magnitude corresponding to that obtained by other studies [12, 15, 16, 37]. Differences in the estimation can be ascribed to different calibration and testing contexts. Indeed, almost all the car-following models are calibrated on straight stretches of road, in which drivers’ behaviour is different from that observed at roundabouts.

Random terms of the model ($\varepsilon_n(t)$) are normally distributed with a mean equal to -0.047 (m/s$^2$) and standard deviation equal to 0.237 (m/s$^2$). Further information about the model and the estimated parameters are described in Guido and Vitale [38].
3.3 Risk analysis

In order to estimate traffic conflicts, reactions of following vehicles’ were observed in specified sections of the roundabout and then were compared to the estimated ones obtained from the model.

These reactions, expressed in terms of deceleration rate, were analyzed on the basis of the expected values of Deceleration Rate to Avoid the Crash (DRAC). DRAC was defined in terms of the speed differential between following vehicle and lead vehicle divided by their closing time [39], and for rear-end interactions this can be expressed as:

\[
DRAC_n(t) = \frac{(V_n(t) - V_{n-1}(t))^2}{\Delta X_n(t) - L_{n-1}}
\]  

(12)

DRAC values were classified according to Hydén [40] to identify braking levels and verify if the observed and the estimated reactions were properly applied by users.

Therefore, six conflict levels were established depending on DRAC values: 1) DRAC equal to 0 m/s² – evasive action not necessary; 2) DRAC ranging from 0 to 1 m/s² – adaptation necessary; 3) DRAC ranging from 1 to 2 m/s² – reaction necessary; 4) DRAC ranging from 2 to 4 m/s² – considerable reaction necessary; 5) DRAC ranging from 4 to 6 m/s² – heavy reaction necessary; 6) DRAC greater than 6 m/s² – emergency reaction necessary. No conflict is expected for the first two levels.

Table 1 shows the number and the percentage of vehicles that applied observed and estimated reactions according to the expected levels of DRAC.

Table 1: Number and percentage of vehicles according DRAC and observed/estimated reactions.

<table>
<thead>
<tr>
<th>Level of conflict</th>
<th>DRAC (m/s²)</th>
<th># veh.¹</th>
<th>% veh.²</th>
<th># obs. veh.³</th>
<th>% obs. veh.⁴</th>
<th># est. veh.⁵</th>
<th>% est. veh.⁶</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>6</td>
<td>1.10</td>
<td>0</td>
<td>0.00</td>
<td>5</td>
<td>83.33</td>
</tr>
<tr>
<td>2</td>
<td>0–1</td>
<td>508</td>
<td>93.21</td>
<td>114</td>
<td>22.44</td>
<td>363</td>
<td>71.46</td>
</tr>
<tr>
<td>3</td>
<td>1–2</td>
<td>24</td>
<td>4.40</td>
<td>22</td>
<td>91.67</td>
<td>24</td>
<td>100.00</td>
</tr>
<tr>
<td>4</td>
<td>2–4</td>
<td>4</td>
<td>0.73</td>
<td>3</td>
<td>75.00</td>
<td>4</td>
<td>100.00</td>
</tr>
<tr>
<td>5</td>
<td>4–6</td>
<td>2</td>
<td>0.37</td>
<td>2</td>
<td>100.00</td>
<td>2</td>
<td>100.00</td>
</tr>
<tr>
<td>6</td>
<td>&gt;6</td>
<td>1</td>
<td>0.18</td>
<td>1</td>
<td>100.00</td>
<td>1</td>
<td>100.00</td>
</tr>
</tbody>
</table>

¹Number of vehicles having DRAC according to conflict levels.
²Percentage of vehicles having DRAC according to conflict levels.
³Number of observed vehicles applying deceleration according to conflict levels.
⁴Percentage of observed vehicles applying deceleration according to conflict levels (column five/column three).
⁵Number of estimated vehicles applying deceleration according to conflict levels.
⁶Percentage of estimated vehicles applying deceleration according to conflict levels (column seven/column three).
A first observation concerns the high percentage of observed vehicles (94.31%) that are not in traffic conflicts according to DRAC classification above described; however, 93.21% of vehicles should adapt their condition to the leader vehicles’ behavior.

The difference found between the observed and the estimated number of vehicles having deceleration ranging from 0 to 1 m/s$^2$ is justified considering the fact that the lower limit of this level of conflict is equal to 0 m/s$^2$, and many observed reactions (accelerations and decelerations) are close to this value. Therefore, the model provided reactions with more occurrences of deceleration compared to those observed, even if the average reactions’ values are close to the real ones.

It should also be emphasized that model replicates well the expected reactions based on the DRAC values. Indeed, for the second level of conflict (DRAC ranging from 0 to 1 m/s$^2$), the model forecasts reactions of following vehicles in terms of deceleration with a percentage equal to 71.46%, while only 22.44% of observed users react applying deceleration, although a necessary adaptation is expected [40].

Concerning the levels of conflict 3, 4, 5 and 6, there are no appreciable differences between the observed values and the estimated ones.

4 Conclusions

The analysis of safety at a roundabout intersection was performed on the basis of traffic conflict technique. Rear-end vehicles’ interactions were evaluated from a frame-by-frame analysis of a video-taped sample of trajectories. This analysis allowed the authors to calibrate a car-following model able to replicate rear-end interactions of the traffic flow. The calibrated behavioural model provided estimates of the users’ reaction to a stimulus produced by the preceding vehicles in the traffic stream.

Furthermore, following and lead vehicles’ pairs were identified from the observed trajectories to assess conflict levels according to Deceleration Rate to Avoid the Crash, a surrogate safety performance measure based on the differential speeds and spacing associated with each vehicle’s pair.

In car-following conditions, potential conflict scenarios occur when the following vehicle reacts with a deceleration lower than a threshold corresponding to a certain value of DRAC. However, the authors classified the levels of conflict on the basis of DRAC [40], and established whether drivers should have applied a suitable reaction. Conflict scenarios derived from the direct observation of vehicles’ reactions were compared with those obtained applying the car-following model.

From the analysis it emerged that 94.31% of observed vehicles were not in traffic conflicts according to DRAC classification, and no reaction was expected, but 93.21% of vehicles should have adapted their condition to the leader vehicles’ behavior being in second level of conflict.

For DRAC ranging from 0 to 1 m/s$^2$ the model forecasts that vehicles adapt their movement with more occurrences of deceleration compared to those
observed; however, since no conflict is expected, observed drivers apply their adaptations with safety margin. Regarding the levels of conflict requiring reactions (levels 3 to 6), there are no appreciable differences between the observed number of vehicles reacting and the estimated ones.

Future developments of the research could be addressed to the transferability of the car-following model and to the analysis of different roundabout’s configurations in order to better investigate safety issues and, consequently, suggest helpful solutions for planners and designers.

References


[40] Hydén C., Traffic safety work with video-processing, Technical report, Transportation Department, University Kaiserslautern, 1996.