Moving from Conventional Roundabouts to Turbo-Roundabouts

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Abstract

This paper introduces the turbo-roundabout concept and compares its performance with the conventional double-lane roundabout in terms of safety and capacity. While researchers agree as to the safety benefits of turbo-roundabouts, improvement in terms of capacity is still open to discussion. The application of a new calculation method shows that only in very specific and rare cases of traffic demand, can a turbo-roundabout be expected to provide more capacity than a double-lane conventional roundabout of similar size.

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1. Introduction

Compared with other traditional at-level intersections, roundabouts respond more efficiently to multiple functions such as traffic regulation, traffic calming, urban regeneration and landscaping, and are particularly popular for enabling fluid traffic operations with increased safety (Bastos Silva, 2004; Brown, 1995; FHWA, 2000). The literature reports accident reductions of between 40% and 70%. However, it was probably the 95% drop in the fatality rate that most contributed to their spread worldwide (Brown, 1995; FHWA, 2000; Hall and Surl, 1981; Maycock and Hall, 1984).

Despite their excellent performance, international experience over the last 40 years has been showing that negotiating a roundabout can be a complex task. Driver indecision and misunderstanding of the driving rules can lead to weaving conflicts and accidents in the circulatory carriageway. These accidents, although not usually severe, are frequent and often affect normal traffic flow.

The turbo-roundabout concept has recently emerged in the Netherlands as a viable alternative to conventional multilane roundabouts, aiming to improve safety conditions. During the last decade several turbo-roundabouts

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have been constructed with good results, mostly in northern European countries. However, the few studies on this subject do not allow definitive conclusions to be drawn about their performance and thus further research is recommended. This paper sets out to contribute to the study of turbo-roundabouts, presenting the concept and comparing it with conventional double-lane roundabouts in the areas of safety and capacity.

2. Operational problems with conventional roundabouts

The conventional multilane roundabout is an efficient solution to cope with variable traffic demand. Additional entry and circulatory lanes increase capacity but they also increase the safety problems. These are mainly related to improper driver behavior at the entrance, circulatory and exit zones, and to the consequent weaving maneuvers within the circle.

Previous studies on two-lane roundabouts confirmed such improper behavior as being common practice, resulting in conflicts and increased likelihood of crashes (Bastos Silva, 2004, 1997). In Portugal, about 40% of drivers who approach the roundabout using the right lane invade the left circulatory lane, thus following a rectilinear path. Additionally, about 20% of the drivers who approach the roundabout using the left lane take the right exit lane, to minimize driving inconvenience (see Fig. 1.).

Poor signage (or pre-signage) also serves to increase drivers’ problems with choosing the approach lane appropriate to the destination in good time.

In Portugal, as in some other countries, conflicts arise because there is no legal framework that specifies the procedures to be adopted to correctly negotiate roundabouts. Consequently, some drivers choose the right lane to take left exits and execute U-turns. This incorrect behavior leads to hesitation and unpredictable maneuvers, resulting in more points of conflict. There are 8 conflict points in a single-lane roundabout and 24 in a two-lane roundabout. However, this number can rise to 32 if we consider incorrect behavior (see Fig. 2). Moreover, the use of multiple circulatory lanes requires increasing carriageway width, which allows higher speeds and makes it harder to maintain adequate deflection.
Some countries have avoided these problems by limiting the adoption of multi-lane roundabouts, for example France (Guichet, 1992; SETRA, 1998), Germany (Brilon, 2005) and Switzerland (Bovy and Dietrich, 1991). The UK (DfT, 2007) and Australia (Austroads, 1993) have been trying to incorporate raised splitters near the entry, in order to ensure higher deflection and lower speed. In spite of this attempt to increase safety, crashes at roundabouts are common and alternative solutions must be sought to solve the problem. With this goal, the turbo-roundabout concept has emerged in the Netherlands.

3. Turbo-roundabout: the concept

The turbo-roundabout concept emerged in the Netherlands in 1996 as the brainchild of Lambertus Fortuijn, a researcher from the University of Delft. It is a variation of the conventional multi-lane roundabout, where drivers are forced to follow a specific path according to their intended destination (see Fig. 3). The carriageway consists of continuous spiral paths, using curbs to separate lanes in the entry, circulatory and exit zones (Mauro and Branco, 2010) – see Fig. 4 and Fig. 5. The installation of curb dividers has two major implications: the elimination of conflict points caused by weaving maneuvers, and speed reduction due to increased deflection (Fortuijn, 2007).

The first turbo-roundabouts were installed in 2000, in the Netherlands. This was followed by their adoption in Poland and most recently in Germany (Brilon, 2005), Finland, Norway and Slovenia. Since then, more than 190 turbo-roundabouts have been implemented in the Netherlands and some design guidelines have been published (CROW, 2008). The Dutch government no longer constructs multi-lane conventional roundabouts, having adopted turbo-roundabouts as current practice (Fortuijn, 2009).
The layout of turbo-roundabouts depends on the traffic demand distribution (CROW, 2008). The dominant flow is the most important factor when choosing the appropriate layout. Fig. 6 presents the most common layouts based on dominant flows, which cover a wide range of traffic situations. Layout A is the best when traffic demand in the secondary lane is low. In this case, the secondary entry can have one (Oval) or two lanes (Standard). When right turns are important the solution can have a bypass (Knee), as shown in layout B. C layout (Spiral) is particularly useful when the through traffic flow is dominant but both the right and left turns are also significant. Finally, layout D is suitable when the traffic demand is evenly spread between the four arms.

![Turbo-Roundabout Layouts](image)

Fig. 6. Turbo-roundabout layouts: (a) Oval; (b) Knee; (c) Spiral; (d) Rotor

4. Safety improvements

Turbo-roundabouts have two principal advantages over conventional double-lane roundabouts, based on the physical separation of the lanes (Corriere and Guerrieri, 2012; Guerrieri et al., 2012): i) reduction in the number of conflict points; ii) speed reduction along the entry, circulatory and exit zones. Several studies suggest a 70% lower crash risk when a double-lane roundabout is converted into a turbo-roundabout (Fortuijn, 2009). Other studies, based on conflict analysis techniques applied to 9 layouts with different demand scenarios, show a 40-50% reduction in the accident rate (Mauro and Cattani, 2010). In a study based on microsimulation applications, Fortuijn (2007) concluded that drivers using the outer lane of a turbo-roundabout drive more slowly than in the double-lane roundabout, with reductions from 48 to 38 km/h. Indeed, one factor responsible for the speed profile of a driver’s through movement is the path curvature (inverse of radius). This is because driving inconvenience increases with centripetal acceleration (AASHTO, 2011), which varies directly with curvature. Raised splitters on turbo-roundabouts force drivers to stay in the correct lane and thus follow paths with smaller radii at slower speeds. This effect can be seen in Figure 7, in which the minimum effort paths are colored according to the curvature. Whereas a driver can ignore lane markings on a two-lane roundabout and choose an almost direct path, keeping their approach speed (path A-C), on a turbo-roundabout all drivers must follow similar paths, resulting in homogeneous low-speed profiles.
Fig. 7. Maximum comfortable path: a) double-lane roundabout; b) turbo-roundabout

Fig. 8. Turbo-roundabout conflict points

In addition to lower speeds, the comparison of the conflict points also suggests improved safety. Comparing Fig. 8 and Fig. 2 we find a reduction from 24 conflict points on the double-lane roundabout to 14 points on the turbo-roundabout, indicating an overall reduction in crash probability. It should be noted, however, that some of these conflicts exhibit higher severity both because of the increased impact angle and because circulating traffic is concentrated in the outer lane. In the absence of historic crash data a deeper analysis is needed, in particular using microsimulation techniques.

5. Capacity improvements

Although the safety benefits are widely recognized there are still doubts about improved capacity. This is essentially because researchers have been using methods that not fully describe the complex interactions between the different traffic streams at multilane roundabouts. For example, Mauro and Branco (2010) and Corriere and Guerrieri (2012) assumed a fixed lane usage at the entries and the irrelevance of traffic distribution in the circulatory lanes. These interactions are fully described in a new calculation method (Vasconcelos et al., 2012a) based on gap-acceptance theory and, specifically, on the generalization of Tanner’s formula for multiple lanes (Hagring, 1998), briefly described here.

The capacity of a single entry lane that merges or crosses a single circulating line is given by:

\[
C = \frac{q_c \phi e^{-\lambda(t_c - \Delta)}}{1 - e^{-\lambda t_f}}
\]  

where \(C\) is the capacity of the entry (veh/s), \(q_c\) is the conflicting flow (veh/s), \(t_c\) is the critical headway (sec.), \(t_f\) is the follow-up time (sec.) and \(\phi, \lambda\) and \(\Delta\) are parameters of the Cowan M3 distribution. In a recent paper (Vasconcelos et al, 2012) conclude that, for Portuguese conditions and assuming a fixed intra-platoon headway \(\Delta = 2\) s, the parameters \(\phi\) and \(\lambda\) can be calculated using formulas (2) and (3), respectively.
\[ \phi = \begin{cases} 
1 & \text{if } q_c < 0.178 \\
1.553(1-2q_c) & \text{if } 0.178 < q_c \leq 0.5 \\
0 & \text{if } q_c > 0.5 
\end{cases} \]  
\tag{2}

\[ \lambda = \frac{\phi q_c}{1 - \Delta q_c} \]  
\tag{3}

For entries with two circulating lanes the capacity is given by equation (4). In this formula the indexes 1 and 2 stand for each of the opposing lanes in the circulatory carriageway (1 – outer lane, nearest the entry; 2 – inner lane, near the circle). The parameters \( \lambda \) and \( \phi \) should be calculated using the formulas (2) and (3), with \( \Delta = 2 \) sec. This formula is used separately for each entry lane. The parameters \( t_e \) and \( t_f \) can take different values according to the entry lane (left/right).

\[ C = \frac{\exp\left[-\left(\lambda_1 + \lambda_2\right)(t_e - \Delta)\right]\left(\lambda_1 + \lambda_2\right)\phi_1\phi_2}{\left(1-\exp\left[-t_f\left(\lambda_1 + \lambda_2\right)\right]\right)(\phi_1 + \lambda_1\Delta)(\phi_2 + \lambda_2\Delta)} \]  
\tag{4}

A sensitivity analysis of Eq. 4 indicates that the maximum capacity is achieved when the opposing traffic is evenly distributed in the circulatory lanes. In fact, this split increases the probability of side-by-side or overlapped circulation, thus reducing the waste of opportunities for the waiting vehicles. Consequently, the application of this formula requires quantification of the opposing traffic for each circulatory lane. This division in turn depends on the lane usage at the other entries, which requires a sequential calculation approach (Vasconcelos et al, 2013) – see Fig.8.

![Traffic distribution](image)

**Fig. 8. Traffic distribution**

Considering, for simplicity’s sake, that there are no U-turn maneuvers, drivers moving from A to B or D use the right lane and the left lane, respectively. Drivers moving to C (through movement) can choose any of the
entry lanes, normally going for the one with the shortest queue to minimize delay. Therefore, in an equilibrium state the lanes have the same level of saturation and the proportion of through traffic using the inner lane is given by:

\[ p_1 = \frac{C_I (q_2 + q_3) - C_O q_i}{q_2 (C_I + C_O)}, p_1 \in [0,1] \]  

(5)

where \( C_I \) and \( C_O \) are the inner (left) and outside (right) lane capacities and \( q_1, q_2 \) and \( q_3 \) are the demand flows for the left, through and right movements respectively. Similarly, the proportion of right-turning traffic using the inside lane at a minor entry of a turbo-roundabout with the layout shown in Fig. 8 is given by (6).

\[ p_i = \frac{C_I q_3 - C_O (q_i + q_2)}{q_i (C_I + C_O)}, p_i \in [0,1] \]  

(6)

The application of this method reveals that the rigid allocation of movements to the entry lanes in the turbo-roundabout’s minor often leads to higher saturation in the left lane and consequently to a waste of the right lane’s capacity (used only for the right turns). This does not happen in the major direction because drivers can select the less congested entry for the through movements. Following this methodology, it can be concluded that turbo-roundabouts offer more capacity than two-lane roundabouts of similar size only in specific and rare circumstances of traffic demand, i.e. when the proportion of right turns in the minor direction is very high (above 60%).

6. Conclusions

The turbo-roundabout solution emerged as a way to solve the safety problems of multi-lane roundabouts. This paper has presented the turbo-roundabout concept, its common layouts and its primary potential uses.

Turbo roundabouts have been compared with two-lane conventional roundabouts in terms of safety and capacity. The geometric features of roundabouts effectively impose minimum deflection levels and speed control, and reduce conflict points, leading to safer operations. These conclusions are consistent with international experience.

In terms of capacity, the results are not consensual. Some authors, using simplified approaches, concluded that turbo-roundabouts offer better capacity than conventional roundabouts of similar size. The application of a new lane-based method reveals that only in very specific scenarios that are uncommon in real-world networks can a standard turbo-roundabout be expected to provide more capacity than the equivalent two-lane roundabout.

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References


Appendix A – Example of capacity calculation

The following example clarifies the sequential calculation procedure to the layout presented in Figure 8. Consider the origin/destination matrix in table A-1 and the critical headways and follow-up times in table A-2.
Table A-1. O/D matrix (vehicles/h)

<table>
<thead>
<tr>
<th>Destination</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0</td>
<td>250</td>
<td>700</td>
<td>220</td>
</tr>
<tr>
<td>B</td>
<td>150</td>
<td>0</td>
<td>190</td>
<td>220</td>
</tr>
<tr>
<td>C</td>
<td>600</td>
<td>50</td>
<td>0</td>
<td>280</td>
</tr>
<tr>
<td>D</td>
<td>250</td>
<td>180</td>
<td>660</td>
<td>0</td>
</tr>
</tbody>
</table>

Table A-2. Gap-acceptance parameters: critical headways, $t_c$ and follow-up times, $t_f$ (s)

<table>
<thead>
<tr>
<th>Main Direction</th>
<th>Secondary Direction</th>
<th>Left</th>
<th>Right</th>
<th>Left</th>
<th>Right</th>
<th>Left</th>
<th>Right</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$t_c$</td>
<td>$t_f$</td>
<td>$t_c$</td>
<td>$t_f$</td>
<td>$t_c$</td>
<td>$t_f$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3.6</td>
<td>2.2</td>
<td>3.9</td>
<td>2.1</td>
<td>3.2</td>
<td>2.2</td>
</tr>
</tbody>
</table>

1. Calculate the opposing (conflicting) flow for each of the entry lanes (Inner, Outer) in the main direction:

\[ q_{\text{cf A,I}} = q_{\text{CB}} + q_{\text{DC}} + q_{\text{DB}} = 890 \text{ veh/h} \]
\[ q_{\text{cf A,O}} = q_{\text{cf A,I}} \]
\[ q_{\text{cf C,I}} = q_{\text{AD}} + q_{\text{BD}} + q_{\text{BA}} = 590 \text{ veh/h} \]
\[ q_{\text{cf C,O}} = q_{\text{cf C,I}} \]

2. Calculate the capacity of each entry lane in the main direction using Eq (1) for one opposing lane (calculations in veh/s):

\[ C_{\text{A,I}} = C|q_{\text{cf}} = 890 \text{ veh/h}, \quad t_c = 3.6 \text{ s}, \quad t_f = 2.2 \text{ s} \]
\[ C_{\text{A,O}} = C|q_{\text{cf}} = 890 \text{ veh/h}, \quad t_c = 3.9 \text{ s}, \quad t_f = 2.1 \text{ s} \]
\[ C_{\text{C,I}} = C|q_{\text{cf}} = 590 \text{ veh/h}, \quad t_c = 3.6 \text{ s}, \quad t_f = 2.2 \text{ s} \]
\[ C_{\text{C,O}} = C|q_{\text{cf}} = 590 \text{ veh/h}, \quad t_c = 3.9 \text{ s}, \quad t_f = 2.1 \text{ s} \]

3. For each entry in the main direction, calculate the proportion of through traffic that uses the left lane (Eq. 5) and obtain the entry flows:

\[ p_{\text{A,I}} = p_I |q_{\text{A}} = q_{\text{AD}}, \quad q_2 = q_{\text{AC}}, \quad q_3 = q_{\text{AB}} \]
\[ p_{\text{A,I}} = 0.557 \]
\[ p_{\text{C,I}} = p_I |q_{\text{C}} = q_{\text{CB}}, \quad q_2 = q_{\text{CA}}, \quad q_3 = q_{\text{CD}} \]
\[ p_{\text{C,I}} = 0.706 \]
\[ q_{\text{A,I}} = q_{\text{AC}}p_{\text{A,I}} + q_{\text{AD}} = 610 \text{ veh/h}, \quad q_{\text{A,O}} = q_{\text{AC}}(1-p_{\text{A,I}}) + q_{\text{AB}} = 560 \text{ veh/h} \]
\[ q_{\text{C,I}} = q_{\text{CA}}p_{\text{C,I}} + q_{\text{CB}} = 474 \text{ veh/h}, \quad q_{\text{C,O}} = q_{\text{CA}}(1-p_{\text{C,I}}) + q_{\text{CD}} = 456 \text{ veh/h} \]

4. Calculate the opposing flow for each entry in the secondary directions (index 1 represents the near lane and index 2 the far lane in relation to the yield line)

\[ q_{\text{cf B,I(1)}} = (1-p_{\text{A,I}})q_{\text{AC}} + q_{\text{DC}} = 970 \text{ veh/h} \]
\[ q_{\text{cf B,I(2)}} = p_{\text{A,I}}q_{\text{AC}} + q_{\text{AD}} = 610 \text{ veh/h} \]
\[ q_{\text{cf D,I(1)}} = (1-p_{\text{C,I}})q_{\text{CA}} + q_{\text{BA}} = 326 \text{ veh/h} \]
\[ q_{\text{cf D,I(2)}} = p_{\text{C,I}}q_{\text{CA}} + q_{\text{CB}} = 474 \text{ veh/h} \]
5. Calculate the capacity of each entry lane in the secondary direction. Use Eq. (4) for the left lane (two opposing lanes) and Eq. (1) for the right lane (one opposing lane).

\[ C_{B,I} = C \left[ q_1 = q_{dB,(1)}, \quad q_2 = q_{DB,(2)}, \quad t_c = 3.2 \ s, \quad t_f = 2.2 \ s \right] \quad C_{B,I} = 426 \ veh./h \]

\[ C_{B,O} = C \left[ q = q_{dB,0}, \quad t_c = 3.9 \ s, \quad t_f = 2.1 \ s \right] \quad C_{B,O} = 536 \ veh./h \]

\[ C_{D,I} = C \left[ q_1 = q_{dD,(1)}, \quad q_2 = q_{dD,(2)}, \quad t_c = 3.2 \ s, \quad t_f = 2.2 \ s \right] \quad C_{D,I} = 943 \ veh./h \]

\[ C_{D,O} = C \left[ q = q_{dD,0}, \quad t_c = 3.9 \ s, \quad t_f = 2.1 \ s \right] \quad C_{D,O} = 1275 \ veh./h \]

6. For each entry of the secondary direction, calculate the proportion of right-turn traffic using the left lane (Eq. 6) and obtain the entry flows:

\[ p_{B,I} = p_1 | q_1 = q_{BA}, \quad q_2 = q_{BD}, \quad q_3 = q_{BC} \quad p_{B,I} = 0 \]

\[ p_{D,I} = p_1 | q_1 = q_{DA}, \quad q_2 = q_{DB}, \quad q_3 = q_{DA} \quad p_{D,I} = 0 \]

\[ q_{B,I} = q_{BA} + q_{BD} + p_{B,I} q_{BC} = 370 \ veh./h \quad q_{B,O} = q_{BC}(1 - p_{B,I}) = 190 \ veh./h \]

\[ q_{D,I} = q_{DC} + q_{DB} + p_{D,I} q_{DA} = 840 \ veh./h \quad q_{D,O} = q_{DA}(1 - p_{D,I}) = 250 \ veh./h \]

7. Obtain the saturation rate for each entry lane: \( x = q/C \) (Table A.3).

<table>
<thead>
<tr>
<th>Entry</th>
<th>A (veh/h)</th>
<th>B (veh/h)</th>
<th>C (veh/h)</th>
<th>D (veh/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lane</td>
<td>Left</td>
<td>Right</td>
<td>Left</td>
<td>Right</td>
</tr>
<tr>
<td>q (veh/h)</td>
<td>610</td>
<td>560</td>
<td>370</td>
<td>190</td>
</tr>
<tr>
<td>C (veh/h)</td>
<td>663</td>
<td>609</td>
<td>426</td>
<td>536</td>
</tr>
<tr>
<td>x</td>
<td>92%</td>
<td>92%</td>
<td>87%</td>
<td>35%</td>
</tr>
</tbody>
</table>