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Conversion of a semi-two lanes roundabout into a turbo-roundabout: a performance comparison

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Abstract

In the last years, as regards the functional design of at-grade intersections, near to classic layouts (signal-controlled junctions, roundabouts, etc.) a new solution has born: the “turbo-roundabout”. It is a canalized multilane oval intersection with a non-traversable or partially traversable center island and with a spiral circulatory carriageway. This kind of roundabout is also characterized by a predictable lane use: some direction flows are physically separated by curbs. Several roundabouts with spiraling circular carriageways were built in northern Europe (in particular in Netherlands) and they have further allowed to extend the notable advantages of this functional solution against multilane roundabouts, such as: 1) no lane changing on the circulatory carriageway; 2) no need to yield to traffic flow on more than two lanes; 3) low driving speed along the through movement because of raised lane dividers and, consequently, a high reduction of accident risk. In this paper a careful literature review on turbo-roundabouts is proposed. Furthermore, the Authors examine the potentialities offered by the transformation of an existing semi-two lanes roundabout into a “virtual” configuration of a turbo-roundabout. In particular, they also evaluate and compare the performance parameters in the two configurations by using a microsimulation software. The case study roundabout is placed in the city of Cosenza (Southern Italy) and it is characterized by great problems of congestion during peak hours. Experimental measures of traffic flows (O/D matrixes), critical gaps, queue lengths and approaching and circulating speeds represent input data for calibration procedures. Afterwards, derived calibration parameters are used as input variables for the new configuration of the intersection as a turbo roundabout. The Authors highlight that the conversion of the existing roundabout into a virtual turbo roundabout determine an increase of capacity together with a minimization of the queue lengths.

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Keywords: Turbo-roundabout; microsimulation tool; roundabout capacity; queue length; calibration procedure.

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1. Introduction

In the last decades, roundabouts have been recognized as a safer and more efficient solution than traditional priority junctions\textsuperscript{1,6}. Since some years, a further step towards this research field has been taken by the evolution of multilane roundabouts into the so-called “turbo-roundabouts”, in order to increase both safety and traffic performance of this kind of intersections\textsuperscript{7,9}. Multilane roundabouts are useful when traffic demand is so high that single lane intersections are not adequate in terms of capacity. However, they offer a significant movement freedom to drivers that often adopt incorrect trajectories, thus leading to weaving conflicts and traffic injuries in the circulatory carriageways. Moreover, drivers tend to assume higher speed when cutting trajectories curvature. Previous studies on multilane roundabouts in Portugal\textsuperscript{10,11} showed that drivers in free flow conditions behaved as follows: i) more than 40\% that entered the roundabout using the right lane (outside) followed straight line trajectories, thus invading the left lane; ii) on the contrary, more than 20\% of drivers using the inside lane (on the left) tended to exit from the circulatory carriageways using the right lane, without looking at road marks. This behavior is strictly related to roundabout deflection levels\textsuperscript{2}. Therefore, there is the need of a correct design strategy which takes into account wider carriageways and cross sections at the entry and exit. Turbo roundabouts represent an evolution of roundabout design, which was introduced in Netherlands\textsuperscript{3} in 1996, in order to reduce the previously highlighted problems, increasing the capacity of intersection without affecting efficiency. As regards geometry, turbo roundabouts are characterized by a spiraling circular carriageways with physically separated lanes (with no mountable curbs also on the ring) into which traffic flows are forced to merge. The physical separation of traffic lanes is only interrupted at the entry into the inner circulatory carriageway. This solution implies that drivers have to choose their direction before entering the intersection, thus reducing the number of conflicts points (from 24 for a traditional double lane roundabout with four legs to 14) and, consequently, the risk of side-by-side accidents\textsuperscript{12-14}. The raised line dividers constrain drivers to follow paths with lower radius and to reduce their speed; moreover, speed profiles are highly homogeneous because all drivers must follow the same paths. Despite the safety benefits derived from this solution are well known, more research is needed to analyze capacity improvement and delay reduction. In the light of the above, in this paper a virtual configuration of a turbo-roundabout is proposed as an alternative configuration of an existing semi-two lanes roundabout located in the city of Cosenza (in Southern Italy) in order to evaluate the potential increase of operational performance\textsuperscript{15,16}. Experimental measures of traffic flows (O/D matrixes), critical gaps, queue lengths and speed distributions were used as input data for calibration procedures by a microsimulation software (PTV Vissim)\textsuperscript{17,18}. Microsimulation was implemented by the specification of: i) distribution and assignment of traffic flow in time and space; ii) implementation of circulation rules: approach speed, reduced speed zones, circulatory speed zones and priority rules; iii) setting up of scenarios to be analyzed (choice of geometric and traffic variables). The suitability of the compared intersections was estimated in terms of queue lengths at each entry.

2. Literature Review

Several previous studies confirmed the advantages derived from the implementation of turbo-roundabouts instead of the traditional double lane ones. In particular, in the study conducted by Mauro and Cattani\textsuperscript{19}, the authors evaluated the safety improvement of turbo-roundabouts by applying a potential accident rate model which was based on the concept of potential conflict. Many crash typologies that can occur at an intersection were considered, such as collision for failure to yield, loss of vehicle control, rear-end at entry and circulating-exiting collisions. Results showed that turbo-roundabouts reduce total crashes of about 40-50\%, and injury crashes of 20-30\%. A more recent research\textsuperscript{20} confirmed the previous results, also highlighting the effectiveness of turbo-roundabouts in urban context, where the pedestrian and two-wheeler traffic level is significant. According to the results of before-after studies carried out by Fortuijn\textsuperscript{3} in Holland, the effect of a turbo-roundabout on traffic safety is comparable to that of single lane roundabouts with a reduction of about 70\% of accidents frequency. Also Vasconcelos et al.\textsuperscript{14} confirmed that turbo-roundabouts represent an adequate solution as regards safety because of a consistent reduction of conflict points, although the same authors showed that these last are more severe due to the increased angle between entry and circulating trajectories. In terms of capacity, they concluded that turbo-roundabouts offer better performance than two-lane roundabouts only when the proportion of right-turns at the minor entries right turns is abnormally high.
(above 60%), that is a very specific and rare demand scenario. Silva et al.\textsuperscript{21} evaluated the performance of a turbo-roundabout corridor in terms of capacity and environmental efficiency. The authors found that the turbo roundabout is able to ensure higher capacity than traditional solutions for load levels below 70% (unsaturated conditions). In terms of emissions, turbo-roundabouts have better CO, CO\textsubscript{2} and PM performance when compared with conventional roundabouts for load levels below 80\%. Giuffrè et al.\textsuperscript{9} proposed three case studies of existing roundabouts in the city of Palermo converted into turbo-roundabouts. All these intersections were characterized by i) an irregular shape of both the central island and the circulating lanes, ii) very high traffic flows, iii) high speed of entering vehicles particularly in the night time. Results showed that many benefits may derive from the conversion of existing intersections into turbo-roundabouts, primarily related to safety (in terms of reduction of conflict points and speeds) and to operational performance thanks to an increase of capacity and a better channeling of traffic flows. The benefits deriving from the conversion of existing double lane roundabouts into turbo-roundabouts were also endorsed by Giuffrè et al\textsuperscript{22}. In this research the authors made a comparison between these types of intersections in terms of delay experienced by entering vehicles (and, consequently, in relation to the level of service quality). The entry capacity at intersections was evaluated by applying the Hagring model\textsuperscript{23} based on the gap-acceptance theory. Also suitability domains under undersaturation flow conditions were built. Results highlighted that the turbo-roundabouts under examination performed better than the double lane ones when a significant share of traffic is handled by major roads and low-to-medium traffic flows come from minor roads. Finally, Yperman and Immers\textsuperscript{24} analyzed the capacity increase deriving from the turning of a conventional roundabout into a turbo-roundabout using the Paramics microsimulation model. Authors found a capacity increase between 12 and 20\%, with the performance depending on the traffic distribution adopted. Moreover, a capacity increase of about 30\% was estimated by Engelsman and Ukel\textsuperscript{25} by using a strategic macro-model.

### 3. Case study analysis

The case study roundabout is placed in the city of Cosenza, South Italy. It is located in a strategic position along a busy road. It is a semi-two lanes roundabout with four entries nearly equally spaced between them. The main approaching roads, in Northern and Southern directions, present both two entry lanes. The secondary ones, in Western and Eastern directions, show instead a single entry lane. The inscribed circle diameter is equal to 37.90 m, while the other geometric properties of the roundabout are shown in the following Figure 1a.

![Fig. 1. (a) Roundabout’s geometric features and points of shot; (b) Queue length on the approach A of the roundabout during peak hours](image)

Roundabout’s performance were recorded on field by three cameras (as reported in Figure 1a) on different days in order to get information either during peak hours or low traffic periods for a total of 9 hours of investigation. Traffic flows, queue lengths, approaching delays, time of service and critical gaps were carried out. The O/D matrix (Table 1), during the time slot between 5.30 p.m. and 6.30 p.m., was homogenized in vehicle per hour by means of the following coefficients: i) 1 car = 1 veic; ii) 1 bicycle or motorcycle = 0.5 veic; iii) 1 truck or bus = 2 veic.
Table 1. O/D matrix

<table>
<thead>
<tr>
<th>veic/h</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0</td>
<td>151</td>
<td>1080</td>
<td>144</td>
</tr>
<tr>
<td>B</td>
<td>104</td>
<td>0</td>
<td>153</td>
<td>94</td>
</tr>
<tr>
<td>C</td>
<td>472</td>
<td>75</td>
<td>0</td>
<td>147</td>
</tr>
<tr>
<td>D</td>
<td>72</td>
<td>135</td>
<td>194</td>
<td>0</td>
</tr>
</tbody>
</table>

Considering the O/D matrix in Table 1, it is possible to note that the existing roundabout is characterized by unbalanced flow patterns. In particular, the 80% of traffic stream enters from the approach A, which is the busiest, and crosses over the roundabout towards the approach C. This dominant flow, especially during the peak hours, originates high levels of queuing (see Figure 1b), unequal lane use and a significant reduction of entry capacity.

The queue lengths for each entry, evaluated during the peak period, are reported in Table 2.

Table 2. Queue lengths

<table>
<thead>
<tr>
<th></th>
<th>Adx</th>
<th>Ass</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Queue Length (veic)</td>
<td>6.1</td>
<td>5.4</td>
<td>3.0</td>
<td>1.2</td>
<td>1.2</td>
</tr>
<tr>
<td>Average Queue Length (m)</td>
<td>36.6</td>
<td>32.3</td>
<td>17.7</td>
<td>7.4</td>
<td>7.1</td>
</tr>
<tr>
<td>Max Queue Length (m)</td>
<td>96.0</td>
<td>90.0</td>
<td>54.0</td>
<td>18.0</td>
<td>30.0</td>
</tr>
</tbody>
</table>

4. Conversion of a semi-two lane roundabout into a turbo-roundabout and capacity evaluation

The geometric features of a turbo-roundabout are defined by the so-called turbo-blocks. Each block is generated by a formation of all the necessary radii, which must be rotated in a certain way, in order to obtain the different traffic lanes. The size of radii of a standard turbo-roundabout and the width of the circulatory lane must be selected in order to guarantee a driving speed through the roundabout not exceeding 40 km/h. Figure 2 shows the geometric features of the case study roundabout after its future conversion into a roundabout with a spiral course of the circulatory carriageway.

An analytical model was used to evaluate the capacity of the case study roundabout: this method is based on the traffic flow theory, where the capacity of each entry is related to the circulating traffic flow and the potential
conflicts, immediately before the exit from the roundabout. The same model, based on modified equations of Bovy and Hagring\textsuperscript{26}, was used for the calculation of the hypothetical turbo-roundabout capacity.

The original Bovy method is based on the following equations:

\[
C = \frac{1}{\lambda} \left( 1500 - \frac{8}{9} \cdot Q_g \right)
\]  

(1)

With:

\[
Q_g = Q_C \cdot \beta + Q_U \cdot \alpha
\]  

(2)

Where: \(C\) = entry capacity [veic/h]; \(Q_C\) = circulating traffic flow [veic/h]; \(Q_U\) = exiting traffic flow [veic/h]; \(Q_g\) = disturbance traffic flow [veic/h]; \(\alpha\) = factor of the influence of the exit traffic flow; \(\beta\) = factor related to the number of lanes in the circulatory carriageway; \(\gamma\) = factor related to the number of entry lanes.

Therefore, considering the O/D matrix (Table 1), the geometrical characteristics of the case study roundabout and applying the Bovy method, it is possible to obtain the values of capacity (\(C\)) for each entry, as shown in Table 3.

| Table 3. Entries’ capacity according to original Bovy method |
|----------------|---------|---------|--------|---------|---------|---------|---------|
| \(Q_c\) | \(Q_U\) | \(Q_C\) | \(\alpha\) | \(\beta\) | \(\gamma\) | \(Q_g\) | \(C_{\text{Round}}\) |
| A   | 1375   | 648    | 404    | 0.25   | 0.95   | 0.65   | 546    | 1561   |
| B   | 351    | 361    | 1418   | 0.25   | 0.95   | 1      | 1437   | 222    |
| C   | 694    | 1427   | 342    | 0.21   | 0.95   | 0.65   | 625    | 1454   |
| D   | 401    | 385    | 651    | 0.22   | 0.95   | 1      | 703    | 875    |

Afterwards considering the turbo-roundabout configuration, it is possible to calculate the capacity of each entry applying the Bovy modified equation according to Dutch experiments\textsuperscript{26}, executed in the real environment. As reported by Fortuijn\textsuperscript{26}, the \(\beta\) parameter can be divided into \(b_1\) (related to the inner circulatory traffic lane) and \(b_2\) (related to the outer circulatory traffic lane). The same consideration can be done for the correction factors of the influence of the exit traffic flow “\(a\)” (\(\alpha\) in original equation) which will be different for the two circulatory traffic lanes in the turbo-roundabout. In this way, each traffic lane can be separately evaluated in the calculation.

Therefore, the modified Bovy equation is the following:

\[
C_{E,1} = C_0 - b_m \cdot Q_{R,m} - b_M \cdot Q_{R,M} - a_1 \cdot Q_U
\]  

(3)

\[
C_{E,2} = C_0 - b_2 \cdot Q_{R,Z} - a_2 \cdot Q_{U,N}
\]  

(4)

Where: \(C_0\) is a coefficient equals to 1550; index 1 is related to the left traffic lane at the entry; index 2 is related to the right traffic lane at the entry; \(Q_R\) is the traffic flow in the circulatory carriageway, with index \(m\) related to the smaller of the two intensities of the traffic flow and the index \(M\) related instead to the bigger one; the index \(N\) is related to the intensity of the traffic flow on the inner lane of the circulatory carriageway; index \(Z\) is related to the intensity of the traffic flow on the outer lane of the circulatory carriageway.

Results are summarized in Table 4. It is very important to underline that, using the modified Bovy method, the capacity for each entry lane is calculated separately and the capacity of the multilane entry is the sum of those of individual entry lanes.
Table 4. Entries’ capacity according to modified Bovy equation

<table>
<thead>
<tr>
<th>QC</th>
<th>QR,m</th>
<th>QR,M</th>
<th>b_m</th>
<th>b_M</th>
<th>a_1</th>
<th>a_2</th>
<th>C_E,1</th>
<th>C_E,2</th>
<th>C_Turbo</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>404</td>
<td>-</td>
<td>404</td>
<td>0.68</td>
<td>0.82</td>
<td>0.21</td>
<td>0.14</td>
<td>1083</td>
<td>1128</td>
</tr>
<tr>
<td>B</td>
<td>1418</td>
<td>540</td>
<td>888</td>
<td>0.68</td>
<td>0.82</td>
<td>0.21</td>
<td>-</td>
<td>407</td>
<td>-</td>
</tr>
<tr>
<td>C</td>
<td>342</td>
<td>-</td>
<td>342</td>
<td>0.68</td>
<td>0.82</td>
<td>0.21</td>
<td>0.14</td>
<td>970</td>
<td>1070</td>
</tr>
<tr>
<td>D</td>
<td>651</td>
<td>236</td>
<td>415</td>
<td>0.68</td>
<td>0.82</td>
<td>0.21</td>
<td>-</td>
<td>1006</td>
<td>-</td>
</tr>
</tbody>
</table>

Making a comparison between the results reported in Table 3 and Table 4, it is possible to highlight how the modified Bovy method, according to the latest Dutch guidelines\textsuperscript{26}, assures higher levels of entry capacity for the roundabout after its conversion into a turbo-roundabout. Data reported in Table 5 show the percentage increase of capacity for each roundabout entry transforming the standard roundabout into a roundabout with a spiral course of the circulatory carriageway. As it is possible to see, the percentage capacity increase ($\Delta C$) varies from about 15% for entry D to about 84% for entry B; for the other two approaches $\Delta C$ reaches a value of about 40%.

Table 5 Percentage increase of capacity transforming roundabout into Turbo-roundabout

<table>
<thead>
<tr>
<th>Approach</th>
<th>$C_{\text{Round}}$</th>
<th>$C_{\text{Turbo}}$</th>
<th>$\Delta C$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1561</td>
<td>2211</td>
<td>+41.64</td>
</tr>
<tr>
<td>B</td>
<td>222</td>
<td>407</td>
<td>+83.33</td>
</tr>
<tr>
<td>C</td>
<td>1454</td>
<td>2040</td>
<td>+40.30</td>
</tr>
<tr>
<td>D</td>
<td>875</td>
<td>1006</td>
<td>+14.97</td>
</tr>
</tbody>
</table>

5. Simulation of roundabout scenario

A microsimulation tool was used to confirm what the capacity calculation has suggested. The simulation process was conducted by the use of VISSIM\textsuperscript{®} 7.0 (Figure 3). Considering the data collected during the different recordings (traffic flows, queue lengths, approaching and circulating speeds, time of service and critical gaps), a calibration procedure of VISSIM was carried out, according to Vaiana et al\textsuperscript{17}. The minimization of the queue lengths represents the objective configuration for the simulation procedure of the case study roundabout scenario. As reported by Vaiana et al.\textsuperscript{18} a careful analysis about the most significant input parameters for the variation of output results was implemented in order to set scenarios. In total, 648 scenarios for case study roundabout were composed and analyzed. Therefore, the following parameters were considered: i) assignment of traffic flow using the O/D matrix reported in Table1; ii) choice of speed distribution for approach speed, reduced speed area, circulatory speed and exiting speed; iii) definition of minimum gap and headway for the conflict areas; iv) driver behaviour according to the psycho-physical car-following model realized by Wiedemann ‘74: in this case the default settings were used\textsuperscript{15}. Considering the best scenario, a comparison between the observed and simulated queue lengths was reported in Table 6. It is possible to note that the percentage deviation on each entry ranges between -6.8% and +16.9%.

Table 6. Comparison of observed and simulated queue lengths

<table>
<thead>
<tr>
<th></th>
<th>Adx</th>
<th>Axx</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average observed Queue Length (m)</td>
<td>36.6</td>
<td>32.3</td>
<td>17.7</td>
<td>7.4</td>
<td>7.1</td>
</tr>
<tr>
<td>Average simulated Queue Length (m) [best scenario]</td>
<td>39.1</td>
<td>28.1</td>
<td>15.4</td>
<td>6.2</td>
<td>5.9</td>
</tr>
<tr>
<td>Percentage deviation (%)</td>
<td>-6.8</td>
<td>+13.0</td>
<td>+13.0</td>
<td>+16.2</td>
<td>+16.9</td>
</tr>
</tbody>
</table>

Once calibrated the real case study roundabout scenario, the same setting was used to implement the turbo-roundabout scenario in order to verify the effective improvement in terms of intersection’s performance\textsuperscript{16}.
The results, reported in Table 7, underline how the conversion of this semi-two lanes roundabout into a turbo-roundabout can determine a significant decrease in terms of queue lengths. In particular, a percentage improvement greater than 90% occurs in correspondence with the two entry lanes of the Northern approach, which is the busiest during the peak hours. All this confirms the results obtained with the modified Bovy method used in the previous section and shows that roundabouts with a spiral course of the circulatory carriageway are a good solution in case of unbalanced flow patterns.

6. Conclusions

Turbo-roundabouts represent a new configuration of intersections that offer higher safety levels thanks to their geometric features, primarily related to the shape of the central island (spiraling) and the separation of traffic lanes by curbs (both at entries and at circulating roadway). These features ensure many benefits for drivers safety, such as: the reduction of the number of conflicts points as a consequence to no lane changing on the circulatory carriageway; low driving speed along the through movement and, consequently, an high reduction of accident risk. Moreover, several previous studies showed that turbo-roundabouts offer also higher operational performance than conventional multilane ones, thanks to an increase of capacity and a better channeling of traffic flows. In the light of the above, this paper focused on the evaluation of queue lengths and entry capacity of an existing roundabout converted into a turbo-roundabout. The existing intersection was primarily characterized in terms of geometric features, traffic flows, queue lengths, approaching delays, time of service and critical gaps. In particular, for the case study roundabout the approach A is the busiest (80% of entering traffic). As regards the analysis of roundabout performance in terms of capacity, results highlighted that the conversion of the semi-two lanes roundabout into a turbo-roundabout can determine an increase of capacity for each entry that varies from a minimum of 15% to a maximum of 84% depending on the approach. For the busiest one (approach A) a capacity increase of about 40% was registered. Afterwards, a microsimulation tool was used for the analysis of the virtual new configuration of the intersection in order to verify the effective improvement in terms of intersection’s performance. The findings showed that a reduction of the queue length can be reached; in particular, the percentage improvement was higher than 90% for entries A, C and D. For entry B this value was about 64%. According to the previous results, this research allows to conclude that the proposed solution of turbo-roundabout may increase both safety and operational performance of
the existing roundabout. However, this conclusions are strictly related to the case study intersection. Further research is needed in order to validate results also for other traffic volumes and distributions.

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