TURBO ROUNDABOUTS: MULTICRITERION ASSESSMENT ON INTERSECTION CAPACITY, SAFETY, AND EMISSIONS

Luís Vasconcelos, MSc.
Adjunct Professor, Department of Civil Engineering
Polytechnic Institute of Viseu
Campus Politécnico de Repeses
3504-510 Viseu – Portugal
Phone: (+351) 232 480 500, E-mail: vasconcelos@estv.ipv.pt
(corresponding author)

Ana Bastos Silva, PhD.
Assistant Professor, Department of Civil Engineering
University of Coimbra
Rua Luís Reis Santos - Pólo II
3030-788 Coimbra – Portugal
Phone: (+351) 239 797 100, E-mail: abastos@dec.uc.pt

Álvaro Maia Seco, PhD.
Associated Professor, Department of Civil Engineering
University of Coimbra
Rua Luís Reis Santos - Pólo II
3030-788 Coimbra – Portugal
Phone: (+351) 239 797 100, E-mail: aseco@dec.uc.pt

Paulo Fernandes, MSc.
Graduate Student, Mechanical Engineering
University of Aveiro
Dept. Mechanical Engineering / Centre for Mechanical Technology and Automation (TEMA)
Campus Universitário de Santiago, 3810-193 Aveiro - Portugal
Phone: (+351) 234 370 830, E-mail: paulo.fernandes@ua.pt

Margarida C. Coelho, PhD.
Assistant Professor, Mechanical Engineering
University of Aveiro
Dept. Mechanical Engineering / Centre for Mechanical Technology and Automation (TEMA)
Campus Universitário de Santiago, 3810-193 Aveiro - Portugal
Phone: (+351) 234 370 830, E-mail: margarida.coelho@ua.pt

Submitted for consideration for publication and presentation at the 93rd Annual Meeting of the Transportation Research Board, January 12-16, 2014.
Resubmitted with reviewers comments addressed: November 10, 2013
Total number of words (excluding references): 4741 (text) + 9 (figures/tables) = 6991 words (Max 7000 words).
ABSTRACT

A turbo-roundabout is a variation of the conventional multi-lane roundabout where spiral road markings and raised lane dividers force drivers to follow a very specific path according to their intended destination. This geometry eliminates weaving and cut-in conflicts by guiding drivers continuously from entry to exit. Turbo-roundabouts were conceived with the main aim of improving safety but their practical benefits are relatively unknown. Likewise, the few existing studies on this subject do not allow definitive conclusions to be drawn about their performance concerning delays and emissions, thus further research is needed. This research is focused on using appropriate modeling methodologies to understand the effects of turbo-roundabouts on capacity, safety and emissions, in comparison with conventional single-lane and double-lane roundabouts. The results indicate that turbo-roundabouts have capacity levels comparable to two-lane roundabouts, but are less robust concerning the directional split of the entry traffic; the turbo-roundabouts leads to fewer traffic conflicts, but with a higher degree of severity; concerning emissions, the results show that there are no advantages on implementing turbo-roundabouts when the main concern are CO$_2$ and/or NOx.

KEYWORDS: Turbo-roundabouts, Capacity, Safety, Emissions.
INTRODUCTION AND OBJECTIVES

A turbo-roundabout is a variation of the conventional multi-lane roundabout, where drivers are forced to follow a specific path according to their intended destination. The carriageway consists of continuous spiral paths, using curbs to separate lanes in the entry, circulatory and exit zones. The installation of curb dividers has two major benefits: the elimination of conflict points caused by weaving maneuvers, and speed reduction due to increased deflection (I). On the negative side, raised curbs can make snow removal difficult and may be a risk for motorcyclists (2). The first turbo-roundabouts were installed in 2000, in the Netherlands. Since then, more than 190 turbo-roundabouts have been implemented and the Dutch government no longer constructs multi-lane conventional roundabouts, having adopted turbo-roundabouts as current practice (I). This was followed by their adoption in Poland and most recently in Germany, Finland, Norway and Slovenia (3). There is also a growing interest about this new layout in the United States (4).

Turbo-roundabouts are usually compared with conventional single-lane and two-lane roundabouts at two levels: capacity/delays and safety. In terms of capacity, the results are not consensual. Initial research based on simplified approaches concluded that in general terms turbo-roundabouts offer higher capacity than conventional roundabouts of similar size (5; 6). More recent works indicate that the relative performance of turbo-roundabouts is highly dependent on the demand flows at the major and minor entries (7). A new lane-based capacity method (8) allows quantifying the importance of the directional split at each entry and reveals that only in very specific demand scenarios, that are uncommon in real-world networks, a standard turbo-roundabout can be expected to provide more capacity than the equivalent two-lane roundabout. This happens namely when the proportion of drivers at each entry turning right is abnormally high (usually above 60%).

Regarding safety, despite the lack of quantitative crash data, researchers are more consensual to the benefits of turbo-roundabouts. From a set of before-and-after studies in Holland, Fortuijn (I) concluded that “the measured effect of turbo roundabouts on safety is comparable with that of single-lane roundabouts”. A study from Mauro and Cattany (9), based on conflict analysis techniques, shows a 40-50% reduction in the accident rate relatively to two-lane roundabouts. The comparison of the number of conflict points – 8 in a single lane roundabout, 24 in a two-lane roundabout and 14 in a turbo-roundabout (see Figure 1) also suggests improved safety when compared with the two-lane layout.

FIGURE 1 Types of conflicts at single-lane, two-lane and turbo-roundabouts.
The safety performance of a roundabout can be related to some measure of its operating speeds \((10; 11)\). In addition to the reduction of conflict points (relatively to the two-lane roundabout), turbo-roundabouts also lead to lower entry and circulating speeds. Whereas a driver can ignore lane markings on a two-lane roundabout and choose an almost direct path, keeping their approach speed, on a turbo-roundabout raised splitters force drivers to stay in the correct lane and thus follow paths with smaller radii at slower speeds.

The effect of turbo-roundabouts on pollutant emissions is also unknown. Research in this field has been focused on emission impacts of single-lane and multi-lane roundabouts \((12-14)\). One concern about emissions in turbo-roundabouts is to what extent vehicle’s speed and acceleration/deceleration patterns will vary, since drivers are forced to follow a specific path according to their intended destination. These speed variation occurrences could have a significant impact and reduce potential emissions benefits of that solution.

From the above points it becomes clear that there are few studies on this subject, most of them lack solid field data and follow different methodologies that in some cases lead to contradictory conclusions. In the absence of crash statistics and emissions data a deeper analysis is needed. Recent developments in the fields of microscopic simulation related to safety and emission analysis suggest that these tools, in addition to the classic evaluation of traffic operation and management strategies, can be successfully used to evaluate road safety levels, capacity and emissions of existing and new infrastructures.

Therefore, the motivation for this research is to use the most appropriate microscopic modeling methodologies to understand the capacity, safety and emissions emitted from turbo-roundabouts, comparing them with conventional single-lane and double-lane roundabouts. The hypothesis is that different patterns of circulating traffic, capacity flows and lane selection will have a different effect on emissions and conflict points and thus in their relative performance. In summary, the objectives of this research are: a) to evaluate capacity and delays, b) to assess conflict locations and occurrence rates, c) to quantify emission impacts of turbo-roundabout operations and d) to explore the differences between turbo-roundabouts, conventional single-lane and two-lane roundabouts.

**METHODOLOGY**

**Basic methodological approach**

This multi-criteria assessment is based on the use of microsimulation to describe the functioning of alternative, single-lane, two-lane and turbo-roundabouts under a number of demand scenarios, chosen to represent a wide range of possible real life situations. An existing single-lane roundabout is taken as a reference problem.

The Aimsun software package \((15)\) was the application selected to develop the microsimulation models. It provides default simulation outputs that allow the conventional assessment of the different layouts in terms of capacity and delays. Aimsun also allows exporting full disaggregated trajectory files that can be used by external applications to assess environmental and safety impacts, as described on the following points.

**Capacity and delays**

Travel times and delays are considered major performance measures for transportation systems \((16)\). Each layout affects travel times at two levels: by imposing
different negotiation speeds in free-flow conditions and, mostly, by offering different geometric and operational capacity levels. Two measures of performance were initially considered: the average travel time for the whole simulation period and travel time reliability. Some preliminary tests indicated that the variability of travel times is almost independent of the layout so only the average travel time, between origin and destination centroids, was considered to measure the operational performance of each alternative.

Safety

The core of this new safety assessment approach is a software developed by the Federal Highway Administration (Surrogate Safety Assessment Model - SSAM) (17) that automates conflict analysis by processing vehicle trajectories files produced during the simulation (vehicle's position, speed and acceleration profiles). This approach has all the generic advantages of simulation (possibility of accessing the safety of new facilities before the occurrence of accidents, controlled testing environment, etc.) but has also some limitations: common microscopic simulation models are developed for traffic-flow analyses and lack some features that are essential for safety analyses (e.g. overtaking with opposing flow, lateral movement, U-turns at intersections). Some authors proposed specific procedures to calibrate simulation models for safety assessment (18; 19) but this is still an ongoing research field. The relationship between simulated conflicts and accidents is also not well established. Al-Ghandour et al. (20) found a statically significant relationship between SSAM predicted conflicts and crashes (predicted by analytic regression methods), but recognize the need for additional studies involving the comparison of SSAM outputs with real crash data.

SSAM operates by processing data describing the trajectories of vehicles driving through a traffic facility and identifying conflicts. For each vehicle-to-vehicle interaction SSAM calculates surrogate measures of safety and determines whether or not that interaction satisfies the criteria to be deemed a conflict. In the present analysis the research team use Time-to-Collision (TTC) as a threshold to define if a given vehicle interaction is a conflict and the Relative Speed (DeltaS) as a proxy for the accident severity. Their definition is (21):

- TTC is the minimum time-to-collision value observed during the interaction of two vehicles on collision route. If at any time step the TTC drops below a given threshold (1.5 s in this work, as suggested for urban areas (22)), the interaction is tagged as a conflict;
- DeltaS is the difference in vehicle speeds as observed at the instant of the minimum TTC. More precisely, this value is mathematically defined as the norm of the velocity vectors of the two vehicles, thus accounting for the differences both in the vehicles absolute speeds and headings. Further details about alternative surrogate measures can be found elsewhere (23; 24).

Emissions

To estimate vehicle emissions, the “Vehicle Specific Power” (VSP) methodology (25; 26) was used. This microscopic emissions model was chosen since it allows estimating instantaneous emissions based on a second-by-second vehicle’s dynamics (speed, acceleration and slope), thus taking as input the same trajectory files given by Aimsun (also required by the SSAM module). The VSP values are categorized in 14 modes of engine regime and an emission factor for each mode is used to estimate CO₂, CO, NOₓ and HC emissions from Light Duty Gasoline Vehicles (LPGV<1.4L), Light
Duty Diesel Vehicles (LDDV<1.9 L) and Light Commercial Vehicles (LCV<2.5L).

Because of its direct physical interpretation and a strong statistical correlation with vehicle emissions, VSP has proven to be very useful in estimating micro-scale emissions for both gasoline (25; 26) and diesel vehicles (27). Some previous studies have documented the effective use of VSP in analyzing emission impacts of single and multi-lane roundabouts in urban corridors (12-14).

Equation 1 (25) provides the VSP calculation for both light duty and commercial vehicles:

$$VSP = v\left[1.1.a + 9.81.\sin\left(\arctan\left(\text{grade}\right)\right) + 0.132\right] + 0.000302.v^3$$  
(Equation 1)

Where:

- **VSP** = Vehicle Specific Power (kW/ton);
- **v** = Instantaneous speed (m/s);
- **a** = Instantaneous acceleration or deceleration (m/s²);
- **grade** = terrain gradient (decimal fraction).

Total emissions for passenger cars were calculated considering 45% of LDGV, 34% of LDDV and 21% of LCV (28). Due to the flat terrain the effect of road grade is negligible. CO₂, CO, NOₓ and HC total emissions by roundabout type were derived based on time spent in each VSP mode multiplied by its respective emission factor (25-27).

**MODEL DEVELOPMENT**

**Site Selection**

In Portugal, the first turbo-roundabout is expected to be constructed in Coimbra, to replace an existing single-lane roundabout (D = 57 m, circulating lane width = 7.8 m). This roundabout is one of the main entries to the city and it gets occasionally congested during the peak periods. Most legs have one lane, both in the entry and in the exit. The east entry has a slip lane towards the north directions. The west leg serves essentially to access a local park and hence it has a very low traffic). The speeds on the approach legs are relatively low (∼55 km/h).

It was decided to follow a two-stage implementation: in the first, the existing roundabout will be widened and transformed into a conventional two-lane roundabout; in the second, following some months to allow driver adaptation, the splitter islands and the inner circle will be reshaped to the final turbo-roundabout layout (Figure 2).
FIGURE 2 Choupal Rbt. in Coimbra – existing layout (left), proposed two-lane (center) and turbo (right) layouts (north direction upwards).

The two-lane layout was designed according to the Portuguese design guidelines (29). Due to some space restrictions the east and west exits are single lane; in the north and south exits there are two lanes during a limited length that may be extended in the future. The design of the turbo-roundabout was based on the Dutch guidelines (30; 31).

The simulation area is centered on the intersection and extends roughly 150 m on each direction. This allows simulating the upstream queues while minimizing the influence of nearby intersections in the simulation outputs.

Traffic demand

A typical week day, 24 h period, was chosen as the modeling period in order to cover a wide range of traffic conditions and to ensure that, regardless of the scenario tested, no vehicles would be retained in the centroids at the end of the simulation period. Traffic flows and speeds at the north and south legs (separately for each direction), were recorded continuously with pneumatic tubes and microwave detectors (Figure 3) and associated with directional splits observed from video recordings to produce 1-hour origin-destination (OD) matrices for the whole 24 h period, totaling 23816 vehicles/day. The origin-destination matrix, in proportional terms, is reasonably constant during the day, with negligible U-turns. For each entry, the left, trough and right directional splits are: South – 4%, 61%, 35%; East – 38%, 2%, 60%, North – 43%, 56%, 1%, West - 30%, 50%, 20%.
Currently, the roundabout has spare capacity during most periods. This happens due to several reasons: first, as shown on Figure 4, the demand peaks of the north and east entries do not overlap; second, the slip lane at the east entry allows right turns without opposing traffic; finally, there is almost no traffic from the south entry going left or making U-turns, which facilitates the entries from the north approach.

FIGURE 3 Choupal Rbt (Coimbra). Left: aerial view (source: Google Maps), Right Top: installation of pneumatic detectors to obtain 24h flow and speed data, Right Bottom: video recordings to obtain directional splits.

FIGURE 4 24h entry flows.
Calibration

The model was calibrated in two steps. The first addressed the parameters of the Gipps car-following model related with steady-state operations and consisted on fitting the model’s macroscopic relations to the speed-flow data collected with the microwave sensor. A new methodology that extended previous calibration techniques in order to properly account the effect of drivers’ desired speed on the steady-state traffic stream behavior was followed. The second set is mostly related to interrupted flow and driver behavior at intersections (maximum acceleration, normal deceleration, reaction time at stop and maximum give way time). To optimize these parameters a procedure based on a genetic algorithm was implemented in Matlab having as objective function the minimization of the differences between observed and simulated density time-series in one-minute intervals. The full details on the calibration process are described elsewhere (32).

EVALUATION FRAMEWORK AND RESULTS

Scenarios

The main objective of the evaluation framework was to obtain quantitative measures that allowed identifying the relative merits of each layout. We assumed that more than to obtain accurate absolute performance indicators, it was important to understand the circumstances under which a layout may be preferable to others. For this task two main demand scenarios were defined: the first evaluates how the performance indicators change with increasing traffic demand, assuming no changes on the directional splits at the entries; the second evaluates the performance of the different layouts under different directional splits, assuming no changes on the total entry flow at each entry.

Capacity and delays

Since both two-lane conventional roundabouts and turbo-roundabouts have two lanes per entry, one should naturally expect them to offer increased capacity when compared with the existing single-lane layout. However, the capacity differences between the conventional and turbo-roundabout layouts are not so obvious. Actually, there are some geometric and functional differences that affect capacity: i) on a normal roundabout the outer circulatory lane at the major entries (north and south, in the specific case of Choupal Rbt.) is used by part of the through movements (east-west and west-east); on a turbo-roundabout the opposing traffic is concentrated in a single lane, which reduces the number of large gaps available for the vehicles waiting at the yield line. ii) on a normal roundabout drivers in the right lane of the minor entries are affected by all circulating vehicles, even if the trajectories do not actually intersect (10; 33). On a turbo-roundabout the right lane at the minor entries (east / west) is used only to turn right and the opposing traffic is reduced since part of the through traffic (north-south or south-north) is physically separated at the exit. iii) while right-turning traffic must use the right entry lane on the normal roundabout, both left and right lanes can be used at the minor entries of a turbo-roundabout to make that movement.

For the first scenario, and for each layout, seven demand levels were simulated, each one for a 24 h period. Figure 5-a depicts the average travel time (origin to destination) for the first demand scenario. Under the existing demand (global demand factor = 100%) the three geometries operate below capacity and drivers suffer similar
delays due to random queuing. The single-lane roundabout is able to receive additional
traffic (∼30%) before congesting. The two-lane and the turbo layouts continue operating
below capacity for the whole range of tested flows.

To test the sensitivity of the delays to the directional splits the total demand at
each entry was assumed constant (equal to the observed), the traffic split was assumed
identical for all entries and the entry proportions were varied in 12.5% steps covering all
possible traffic splits (45 combinations for each layout; for simplicity no U-turns were
considered).

Figure 5-b indicates that, for all layouts, the minimum travel times are obtained
when all vehicles are turning right and the maximum occur when all vehicles are turning
left, which is obviously related to the increase of the opposing flow at each entry. Both
the two-lane and the turbo-roundabouts are more robust solutions (that is, they allow a
wider range of traffic splits without congesting), but the conventional two-lane layout
operates below capacity for almost every tested combination. These results are
consistent with a previous work based on analytic gap-acceptance formulas in which it
is shown that a turbo-roundabout can be expected to offer more capacity than a two-lane
roundabout only if the proportion of right turning traffic from the minor entries is very
high (8).

Considering the specific case of Choupal Rbt., it can be concluded that the
conversion to a turbo-roundabout will maintain the current uncongested operations and
thus will have no major effect on the actual delays, unless traffic grows significantly or
traffic splits at the entries are drastically changed (particularly leading to an increase of
left turns).

![Travel time (s)](attachment://figure5.png)

**FIGURE 5** Travel times: a) for increasing traffic demand factors; (b) for different directional splits
at the entries (s).
Safety

The effects of both the uniform traffic growth and the directional splits are analyzed at three levels: traffic growth – 100% (observed), 130% and 150% demand factors; directional splits: 60-20-20, 20-60-20 and 20-20-60 (percentages of right turning, through and left turning movements, respectively). Figure 6 illustrates these conflicts for the second demand scenario, case 20-60-20, indicating the concentration of conflicts on the most heavily congested entries (north and east) and the predominance of weaving conflicts on the two-lane layout.

SSAM outputs are summarized on Table 1. The first half of the table refers to the effect of the total demand traffic. Several conclusions can be drawn: i) as expected, the number of conflicts increases with the total traffic with all layouts; results from additional simulations (not shown here) indicate an exponential growth with traffic, which agrees with conventional accident prediction models (34); ii) the two-lane roundabout is the worse solution both in the number and severity of conflicts, mostly due to the weaving and exit-circulating maneuvers; iii) the turbo-roundabout, compared with the single-lane solution, has fewer conflicts, but these are more severe, due to the increased angle between entry and circulating trajectories;

The second half refers to the effect of the directional split at the entry. This set of results also allows drawing some conclusions: i) the number of conflicts tends to increase with the proportions of left-turning traffic which is obviously related with the increase of entering-circulating encounters. However, this relation does not hold for the two-lane roundabout: there are less conflicts in the 20-60-20 split than with 20-20-60, which suggests that the reduction of weaving and exit-circulating conflicts at the exits compensates the increase of rear-end and entry-circulating conflicts at the entries; ii) the average relative speeds, taken as surrogate for the severity, are higher when most vehicles are turning right. Although counter intuitive, this result is related to the...
reduction of the circulating traffic which allows a higher percentage of vehicles entering
to the roundabout at their desired speeds, originating conflicts with the circulating
vehicles at higher speeds.

These results agree, in general terms, with expectations and with crash data
experiences. However, we must emphasize that SSAM is still an emerging safety
assessment method and that the relation between simulated conflicts and real accidents
is not well determined yet.

**TABLE 1 Safety measures: total number of conflicts and average relative speeds.**

<table>
<thead>
<tr>
<th>Demand Factor (%)</th>
<th>Number of conflicts</th>
<th>Avg. relative speed (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>143</td>
<td>329</td>
</tr>
<tr>
<td>130</td>
<td>532</td>
<td>828</td>
</tr>
<tr>
<td>150</td>
<td>936</td>
<td>1303</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Directional Split (%)</th>
<th>Number of conflicts</th>
<th>Avg. relative speed (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>60-20-20</td>
<td>145</td>
<td>202</td>
</tr>
<tr>
<td>20-60-20</td>
<td>752</td>
<td>638</td>
</tr>
<tr>
<td>20-20-60</td>
<td>1251</td>
<td>587</td>
</tr>
</tbody>
</table>

**Emissions**

In this section VSP mode distributions of each roundabout for all scenarios are
presented. Further, emissions impacts (CO₂, CO, NOₓ and HC) of two-lane and turbo-
roundabouts are compared with the single-lane roundabout.

**VSP Mode Distributions**

Figure 7 (a-f) illustrates the percent time spent in each VSP mode for each roundabout,
and all scenarios analyzed. These VSP modes are later used to estimate the emissions
generated for each roundabout.

On average vehicles spent most of the time on VSP modes 1, 3 and 4 which
corresponds to vehicles decelerate as they approach the roundabout, enter the circulating
lanes and accelerate as they exit the roundabout. As expected, the percentage of VSP
mode 3 (idling or low-speed situations) increased with the demand factor (see Figure 7-
b and 7-c). This was particularly noticeable on single-lane roundabout whose
contributions of VSP mode 3 enhanced of almost 8% from a 100% of traffic demand to
a 150% of traffic demand. It should be also emphasized that in a two-lane roundabout,
compared with the turbo-roundabout solution, vehicles spent less time in VSP mode 3,
but there is a higher percentage of time spent in acceleration modes (from VSP 4 to 14).

Concerning the directional split scenarios (see Figure 7, d-f), the VSP mode
distributions of three roundabouts were similar when 60% of vehicles turn right and
through. However, when most of vehicles turn left, significant differences were found.
For this scenario, 37% of time in single-lane roundabout is spent in VSP mode 3.
Turbo-roundabout also achieved a significant increase in VSP mode 3, namely when
compared with the two-lane solution. Nevertheless, VSP modes 4 to 6 were more
expressive on that solution.
Comparison of emission impacts

In this section the emission impacts of single-lane, two-lane and turbo-roundabouts were compared for different traffic demands and turn rate scenarios.
Considering the 100% demand factor scenario, significant differences between two-lane and single-lane roundabouts were observed (see Table 2). The introduction of the two-lane conventional roundabout could save up to 17% for both CO$_2$ and NO$_X$ emissions and 21% in CO emissions. Turbo-roundabout showed particularly effective in terms of local pollutants emissions: it leads to an average CO and HC emissions reduction of 24% and 33%, respectively. This was explained by the lowest acceleration and deceleration rates experienced by drivers on that solution (see Figure 7-a) which are especially relevant for CO emissions.

Regarding the 150% demand factor scenario, the difference in the amount of emissions among three solutions increased in relation to lower demand factors. In fact, the two-lane roundabout yielded the highest CO$_2$ and NO$_X$ emissions reduction, by 21% and 19%, respectively. From a CO and HC criterion, the results pointed out the turbo-roundabout as the better environmental solution (-18% for CO and -34% for HC).

Concerning the directional split scenarios, the results showed that if 60% of approaching vehicles turn right they emit less CO$_2$ in two-lane roundabout, when compared with other solutions. Analyses of remaining directional split scenarios (20-60-20; 20-20-60) resulted in same conclusions for two-lane roundabout. As displayed in Figure 5, turbo-roundabout offers less capacity than a two-lane when there is no traffic right turn, and most particularly when vehicles want to turn left (20-20-60). At the emissions level, the results obtained also confirmed these findings. CO$_2$ emissions differences between two-lane and turbo-roundabout are larger for low rates of right turn. When 60% of vehicles go through and left they produced an amount of CO$_2$ up to 6% more in the turbo-roundabout when compared with the two-lane solution. By assuming that all movements were made to the right direction, this difference decreased to 3%.

NO$_X$ follows the same trend of CO$_2$, when the results between two-lane and turbo-roundabouts are compared, which means that the implementation of a turbo-roundabout does not lead to a reduction of these two gases. Nonetheless, CO and HC emission savings on turbo-roundabout are more significant (-13% and -38%, respectively) in the 20-20-60 directional split scenario.
TABLE 2 Variation of emissions per roundabout type in relation to the single-lane roundabout for all scenarios during a 24 h period.

<table>
<thead>
<tr>
<th>Demand Factor (%)</th>
<th>Roundabout Type</th>
<th>Emissions (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CO₂</td>
<td>CO</td>
</tr>
<tr>
<td>100</td>
<td>3001.21</td>
<td>20.44</td>
</tr>
<tr>
<td></td>
<td>-17%</td>
<td>-21%</td>
</tr>
<tr>
<td></td>
<td>-15%</td>
<td>-24%</td>
</tr>
<tr>
<td>130</td>
<td>3886.40</td>
<td>25.73</td>
</tr>
<tr>
<td></td>
<td>-15%</td>
<td>-15%</td>
</tr>
<tr>
<td></td>
<td>-14%</td>
<td>-19%</td>
</tr>
<tr>
<td>150</td>
<td>4800.46</td>
<td>29.86</td>
</tr>
<tr>
<td></td>
<td>-21%</td>
<td>-15%</td>
</tr>
<tr>
<td></td>
<td>-19%</td>
<td>-18%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Directional Split (%)</th>
<th>Roundabout Type</th>
<th>Emissions (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CO₂</td>
<td>CO</td>
</tr>
<tr>
<td>60-20-20</td>
<td>2576.73</td>
<td>13.06</td>
</tr>
<tr>
<td></td>
<td>-11%</td>
<td>-13%</td>
</tr>
<tr>
<td></td>
<td>-8%</td>
<td>-11%</td>
</tr>
<tr>
<td>20-60-20</td>
<td>2899.02</td>
<td>18.81</td>
</tr>
<tr>
<td></td>
<td>-14%</td>
<td>-15%</td>
</tr>
<tr>
<td></td>
<td>-8%</td>
<td>-14%</td>
</tr>
<tr>
<td>20-20-60</td>
<td>3751.45</td>
<td>18.05</td>
</tr>
<tr>
<td></td>
<td>-29%</td>
<td>-7%</td>
</tr>
<tr>
<td></td>
<td>-23%</td>
<td>-13%</td>
</tr>
</tbody>
</table>

CONCLUSIONS

This research explored the effect of turbo-roundabouts on capacity, conflict locations and emissions generated from vehicles. A microscopic simulation approach was followed to identify the consequences of converting an existing single-lane roundabout to a two-lane roundabout and after to a turbo-roundabout.

Results indicate no relevant differences on travel times when operating below capacity levels and a fast increase afterwards. The single-lane roundabout is the layout that offers the least capacity. Both the two-lane and turbo-roundabouts have two entry lanes per approach, thus offering additional capacity. Drivers on a conventional two-lane roundabout have more flexibility to select the entry lane, allowing a wider range of traffic splits before congestion occurs. Turbo-roundabouts offer more capacity than a two-lane roundabout only under very specific and rare demand scenarios, namely when the proportion of right-turns at the minor entries right turns is abnormally high (above 60%).

The SSAM methodology was followed to estimate the safety of the three alternatives. The two-lane roundabout is the worse solution both in the number and severity of conflicts, mostly due to the weaving and exit-circulating maneuvers. The turbo-roundabout, compared with the single-lane solution, has fewer conflicts, but these are more severe, due to the increased angle between entry and circulating trajectories.

Total emissions of vehicles moving through the roundabout were further compared. By using VSP methodology taking into account speed trajectories from Aimsun model, this paper estimated the second-by-second emission generated from the vehicle during different acceleration-deceleration cycles. The results show that turbo-roundabouts produced more CO₂ and NOₓ emissions, when compared with two-lane roundabouts, thus there is no advantage on the implementation of turbo-roundabouts if the major concern in a certain region is related, for instance, with NOₓ pollution levels.
If the priority is the reduction of CO\(_2\) emissions, a two-lane roundabout is a better choice, but for other local pollutants (CO and HC) there is an advantage of a turbo-roundabouts.

Overall it becomes clear that when, namely and most commonly, due to capacity considerations, it is necessary to implement a two-lane roundabout in alternative to a single-lane one, a turbo-roundabout will probably be the best option unless a maximum output capacity is needed.

ACKNOWLEDGMENTS

This work has been carried out in the framework of projects EMSURE - Energy and Mobility for Sustainable Regions (CENTRO-07-0224-FEDER-002004) and AROUND (FCT project PTDC/SEN-TRA/122114/2010). TEMA team also acknowledges to FCT Project PTDC/SEN-TRA/113499/2009, Strategic Project PEst-C/EME/UI0481/2011 and FLAD – Luso American Foundation. P. Fernandes acknowledges the support of FCT for the Scholarship SFRH/BD/87402/2012.

REFERENCES


