Transport

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Vasconcelos, Silva and Seco

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Capacity of normal and turbo-roundabouts: comparative analysis

1 **António Luís Pimentel Vasconcelos** MSc
Assistant Professor, Civil Engineering Department, Polytechnic Institute of Viseu, Viseu, Portugal

2 **Ana Bastos Silva** PhD
Assistant Professor, Civil Engineering Department, University of Coimbra, Coimbra, Portugal

3 **Álvaro Jorge da Maia Seco** PhD
Associate Professor, Civil Engineering Department, University of Coimbra, Coimbra, Portugal

While researchers agree as to the safety benefits of turbo-roundabouts, their improvements in terms of capacity and delay remain open to discussion. This is mostly because previous research is based on capacity models that do not fully describe the complex interactions between traffic streams on multi-lane roundabouts. This paper proposes a procedure to calculate capacity based on gap-acceptance theory. It addresses the limitations mentioned by accounting for usually disregarded effects such as the dynamic choice of the entry lane and unequal allocation of traffic in the circulatory lanes. Capacities were calculated for a wide range of demand scenarios and it has been shown that only under demand scenarios that are very specific and uncommon in real-world networks, associated with very high percentages of right-turning entry traffic, can a standard turbo-roundabout be expected to provide more capacity than the equivalent two-lane roundabout. It has also been shown that two-lane roundabouts can normally be expected to provide capacities of 20–30% above those of comparable turbo-roundabouts.

Notation

C_k	capacity of entry lane k
I_k	set of priority streams for entry lane k
p_I	proportion of through traffic using the inside entry lane (normal roundabouts) or proportion of right-turning traffic using the inside entry lane (turbo-roundabouts)
$q_{\mathrm{cf},i}$	opposing traffic at approach lane i
q_x	demand flow at approach leg x
q_{xy}	demand flow (from x to y)
t_c	critical headway
t_f	follow-up time
x_i	saturation ratio of entry lane i
Δ_i	intra-platoon headway in stream i
λ_i	scale parameter of Cowan's M3 distribution in stream i
ϕ_i	proportion of free headways in stream i

1. Introduction

Many studies have shown that roundabouts are safe and efficient solutions, especially when single-lane roundabouts are compared with conventional priority junctions (Elvik, 2003; Rodegerdts *et al.*, 2010). However, single-lane roundabouts often provide insufficient capacity and roundabouts with two or three circulatory lanes are required. Selecting the correct entry and circulatory lane on multi-lane roundabouts is not always trivial. Driver indecision and difficulties in interpreting the roundabouts' driving rules can lead to weaving conflicts and accidents in the circulatory carriageway. Although these accidents are usually not serious, they are common and often affect the normal flow of traffic. Multiple circulatory lanes also require wider carriageways with the extra width often being used by drivers to cut the trajectory curvature and negotiate the roundabout at higher speeds, disregarding lane markings.

In a study of standard two-lane roundabouts conducted in Portugal (Silva and Seco, 2005; Silva *et al.*, 2006) it was found that more than 40% of drivers in free-flow conditions that entered the roundabouts using the outside lane (right, near the sidewalk) followed straight line trajectories, with the consequent invasion of the left circulatory lane (in this paper right-hand driving is assumed). A similar thing happened in the inside lane (left, near the splitter island) trajectories: more than 20% of drivers opted to leave the roundabout using the right circulatory lane, disregarding the road marking indications. This behaviour was found to be highly related with roundabout geometry and, specifically, with the level of deflection: the inexistence of physical elements that impose swift trajectory changes results in greater acceptance by drivers in maintaining their circulation lane but also results in behaviour patterns characterised by high entry speeds and by behavioural heterogeneities that tend to persist along the crossing and exit zones. On the other hand, the usage of high deflection levels tends to impose high levels of discomfort that induce drivers to invade adjacent lanes searching for more direct and comfortable trajectories.

Geometrical parameters have, consequently, a direct bearing on roundabout safety. Montella (2011) showed that the deflection radius and the entry angle are the two most important geometrical factors that contribute to crash frequency. These problems have led countries such as Germany (Brilon, 2011), France (Setra, 1998) and Switzerland (Bovy *et al.*, 1991; Lindenmann, 2006) to use multi-lane roundabouts only under exceptional conditions.

In order to address these problems, the turbo-roundabout concept was developed and introduced in Holland in 1996 (Fortuijn, 2009a). A turbo-roundabout has spiral road markings and raised lane dividers, forcing a spiralling flow of traffic. This geometry completely eliminates weaving and cut-in conflicts by guiding drivers continuously from entry to exit (see Figure 1). This principle is conceptually essentially the same as spiral roundabouts, used in the UK, which use spiral lane markings in the circulatory carriageway to direct drivers (DfT, 1997). The main difference consists in the use of raised lane dividers that prevent drivers from using the full carriageway width to reduce curvature, thus contributing to lower speeds. Researchers agree that the combined effect of these measures makes turbo-roundabouts safer than multi-lane roundabouts: in Holland, a before-and-after study showed that, although offering significantly higher capacities, 'the measured effect of turbo-roundabouts on safety is comparable with that of single-lane roundabouts' (Fortuijn, 2009a). Mauro and Cattani (2010) studied the safety of normal and turbo-roundabouts using a model based on the concept of potential conflict and concluded that turbo-roundabouts reduce the total number of potential accidents by between 40% and 50%, and cut the number of potential accidents with injuries by between 20% and 30%. Tollazzi *et al.* (2011) note that, although no formal evaluation of safety had been undertaken, 'turbo-roundabouts in Slovenia have met the expectation as concerns the large capacity and particularly the high levels of traffic safety'. Giuffrè *et al.* (2011) described the conversion of three roundabouts in Palermo, Italy, into turbo-roundabouts. A functional analysis concluded that the conversion resulted in benefits both for operational conditions (good channelling for traffic flows and sometimes an increase of capacity) and safety (reduction of conflict points and moderate speeds).

While the safety benefits are widely recognised, improved capacity and delay are not. This is essentially because researchers have been using methods that do not fully describe the complex interactions between the different traffic streams of multi-lane roundabouts. For example, besides the results reported by Giuffrè *et al.* (2011), Yperman and Immers (2003) also reported global capacity gains of 12–20%. Their analysis was supported by a Paramics micro-simulation model calibrated upon the Swiss roundabout capacity model (Bovy *et al.*, 1991). However, it can be argued that the Swiss model is regression-based and thus

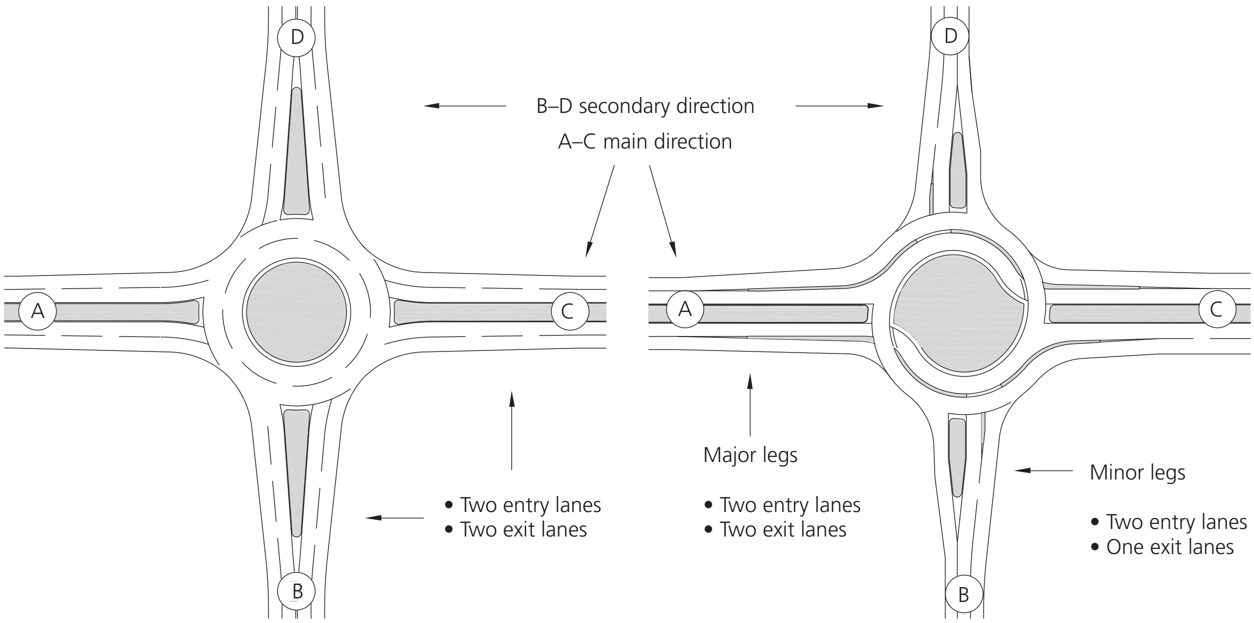

Figure 1. Analysed layouts: (a) normal roundabout and (b) turbo-roundabout

unable to guarantee accurate capacity predictions when the geometric and operational conditions are outside its calibration domain. Engelsman and Uken (2007), meanwhile, used the 'quick-scan' model, which is a strategic macro-model developed by the province of South Holland, and estimated capacity gains for turbo-roundabouts to be between 25% and 35%.

Mauro and Branco (2010) recently developed a robust analysis based on gap-acceptance theory. In their study, capacity calculations are lane-based, according to a formula developed by Wu (2001). Several demand scenarios were studied and it was concluded that, in most of the cases analysed, a turbo-roundabout has advantages over a conventional one in terms of performance levels. It was also concluded that the capacity benefits are very different for the main and the secondary direction entries. Despite the fact that this methodology represents a breakthrough in relation to previous ones, it still leaves room for important improvements.

- Wu's (2001) generic capacity model is used with the same simplifications that were assumed for its integration in HBS 2001 (FGSV, 2001) (the German equivalent of the *US Highway Capacity Manual*). These simplifications consist of making the model insensitive to the traffic flow allocation to the different circulatory lanes in front of each entry (thus depending only of the total opposing flow) and using a simple linear bunching expression to describe the headway distribution in the opposing flow.
- The proportion of traffic that selects a given entry lane when alternatives are available (through movements on normal roundabouts; right-turn movements on turbo-roundabouts) was assumed to be fixed. In the real world, however, drivers have various strategies to select the entry lane depending on how aware and aggressive they are, which tends to result in different operational conditions in different sites and entrances.
- The capacities were compared taking as reference a double-lane conventional roundabout with only one lane per exit, in one direction (compact roundabout). With this layout, circulating drivers are forced to weave into the outer lane, leading to low usage of the inner entry lane. Although this is not an unusual layout, in many countries – including Portugal – the number of lanes in the circle and at the exits is the same, even if only for a limited length of road, which allows drivers to leave the roundabout without changing lane.

The current paper presents a method that addresses these limitations and provides a more generic and accurate estimation and comparison of capacity at both normal and turbo-roundabouts.

2. Capacity model

The capacity model used in this paper is based on Hagring's generic capacity formula for a minor stream crossing or merging independent major streams, each having a Cowan's M3 headway distribution (Hagring, 1998)

$$C_k = \frac{\exp\left(-\sum_{i\in I_k}\lambda_i(t_{c,i}-\Delta_i)\right)\sum_{i\in I_k}\lambda_i}{1-\exp\left(-\sum_{i\in I_k}t_{f,i}\,\lambda_i\right)}\prod_{i\in I_k}\frac{\phi_i}{\phi_i+\lambda_i\Delta_i} \quad (1)$$

where k is the minor stream index, I_k is the set of major streams i conflicting with the minor stream k, ϕ_i, Δ_i and λ_i are the parameters of the headway distribution for each of the opposing lanes, and $t_{c,i}$ and $t_{f,i}$ are, respectively, the critical headway and the follow-up headway for each opposing lane i at entry lane k.

The particular cases for one and two opposing lanes are given by Equations 2 and 3 respectively

$$C = \frac{q\phi\exp\left[-\lambda(t_c-\Delta)\right]}{1-\exp(-\lambda t_f)} \quad (2)$$

$$C = \frac{\exp\{-[\lambda_1(t_{c,1}-\Delta_1)+\lambda_2(t_{c,2}-\Delta_2)]\}(\lambda_1+\lambda_2)}{1-\exp[-(t_{f,1}\lambda_1+t_{f,2}\lambda_2)]} \times\frac{\phi_1\phi_2}{(\phi_1+\lambda_1\Delta_1)(\phi_2+\lambda_2\Delta_2)} \quad (3)$$

A first relation between the three Cowan M3 parameters (ϕ, λ and Δ) stems from the method of moments (Equation 4), which ensures that the mean of the estimated distribution is equal to the flow q

$$\lambda = \frac{\phi q}{1-\Delta q} \quad (4)$$

A second relation is required to solve the indetermination. This relation, also known as a 'bunching model', indicates the proportion of free vehicles in the traffic stream (not driving in platoons) and can take different shapes such as linear, bilinear or exponential (Akçelik, 2007; Çalışkanelli *et al.*, 2009; Tanyel *et al.*, 2007). A bilinear relation calibrated for the Portuguese roundabouts was used for this analysis (Vasconcelos *et al.*, 2012b)

$$\phi = \begin{cases} 1 & \text{if } q < 0{\cdot}178 \\ 1{\cdot}553(1-2q) & \text{if } 0{\cdot}178 < q \leqslant 0{\cdot}5 \\ 0 & \text{otherwise} \end{cases} \quad (5)$$

The above bunching relation was calibrated assuming an intra-platoon headway parameter $\Delta = 2$ s. Therefore, the model predicts null capacity when one or more opposing lanes have flows above $1/\Delta$ (0·5 vehicles/s or 1800 vehicles/h).

3. Assessment framework

3.1 Scenario definition

The main goal of this analysis was to compare the capacity performance of a conventional roundabout (four double-lane entrances and four double-lane exits) with a turbo-roundabout with similar space requirements (four double-lane entrances, two double-lane exits and two single-lane exits) (see Figure 1). The turbo-roundabout was orientated assuming that most through traffic follows the direction AC. According to the geometric differences, entries A and C were named 'major' while entries B and D were named 'minor'.

The main differences in the layouts that affect the capacity estimations are as follows.

- On a normal roundabout, the outer circulatory lane at the major entries (A and C) is used by part of the through movements (DB and BD); on a turbo-roundabout, the opposing traffic is concentrated in a single lane, which leads to a fall in capacity.
- On a normal roundabout, drivers in the outer lane of the minor entries are affected by all circulating vehicles, even if the trajectories do not actually intersect (Hagring *et al.*, 2003; Rodegerdts *et al.*, 2007). On a turbo-roundabout, the outer lane is used only to turn to the right and the opposing traffic is reduced since part of the through traffic (AC or CA) is physically separated at the exit.
- While right-turning traffic must use the outer entry lane on the normal roundabout, both inner and outer lanes can be used at the minor entries of a turbo-roundabout.

Two main demand scenarios were considered. In both scenarios, three constant demand levels in the major direction were assumed: $q_A = q_C = 500$, 1000 and 1500 vehicles/h with a symmetrical split (left, 25%; through, 50%; right, 25%). In the minor direction, starting from zero, the demand was progressively increased in 10 vehicles/h steps until one of the roundabout entry lanes, either minor or major, reached saturation (demand/capacity ratio $x \geqslant 1$). The following distributions were considered.

- Scenario 1 – symmetrical demand at minor entries: $q_{BD} = q_{DB}$, $q_{BC} = q_{DA}$ and $q_{BA} = q_{DC}$.
- Scenario 2 – anti-symmetrical demand at minor entries: $q_{BD} = q_{DB}$, $q_{BC} = q_{DC}$ and $q_{BA} = q_{DA}$.

The first scenario is typical of a general intersection between a minor and a major road (common on European ring roads) where both directions of the major road attract similar levels of traffic. The second scenario typifies situations where most vehicles from the two minor entries take the same direction on the major road – to get to a shopping mall, for example. The capacity was calculated for each of these two scenarios and demand levels, for every possible combination of traffic splits (left, through and right proportions) in 2% steps, resulting in 3978 combinations.

3.2 Entry and opposing flows

As the capacity calculations are lane-based, a lane allocation procedure of traffic is required. This procedure is based on the assumption that when drivers have a choice of two lanes to reach a given destination they will select the one with the lowest degree of saturation and thus the lowest delay (Fisk, 1991). This behaviour can be expected on urban and suburban roundabouts at peak hours when the majority of drivers know the intersection, are aware of traffic conditions and are actively looking for shorter routes. Therefore, in an equilibrium state, the lanes have equal levels of saturation and the proportion of through traffic using the inner lane is given by

$$p_I = \frac{C_I(q_2 + q_3) - C_O q_1}{q_2(C_I + C_O)}, \quad p_I \in [0,\ 1] \tag{6}$$

where C_I and C_O are the inside-lane and outside-lane capacities and q_1, q_2 and q_3 are the demand flows for the left, through and right movements respectively (for the sake of simplicity, U-turns were disregarded) (see Figure 2). Similarly, the proportion of right-turning traffic using the inside lane at a minor entry of a turbo-roundabout with the layout shown in Figure 1 is given by

$$p_I = \frac{C_I q_3 - C_O(q_1 + q_2)}{q_3(C_I + C_O)}, \quad p_I \in [0,\ 1] \tag{7}$$

It should be noted that this allocation method implies an iterative traffic assignment process: initial p_I values have to be set at each entry to allow the calculation of entry and opposing flows at each entry (q, q_{cf}); then, at each iteration, the new opposing flows are used to update the capacities, resulting in new lane usage factors p_I. In most cases, this process converges rapidly: as a rule of thumb, no more than three iterations are required for p_I to change less than 1%.

3.3 Critical and follow-up headways

The gap-acceptance parameters for normal roundabouts used in this study were estimated from a vast set of field observations at one-lane and two-lane roundabouts in Portugal, using the Siegloch, Raff, maximum likelihood, Logit and Wu methods (Vasconcelos *et al.*, 2012a). It was found that those methods have important specificities that significantly affect the results and therefore the capacity estimates. Parameters from the Siegloch method have been used here since this keeps the closest relation to the capacity formulas (Brilon *et al.*, 1999). The average values are presented in Table 1.

Hagring's generic capacity formula caters for the assumption that each entry lane may have its own gap-acceptance parameters and these may also vary for each of the opposing circulatory lanes. These differences were investigated by Hagring *et al.* (2003) using a generalised version of the maximum likelihood method (Hagring, 2000) based on non-superimposed arrival data. It was

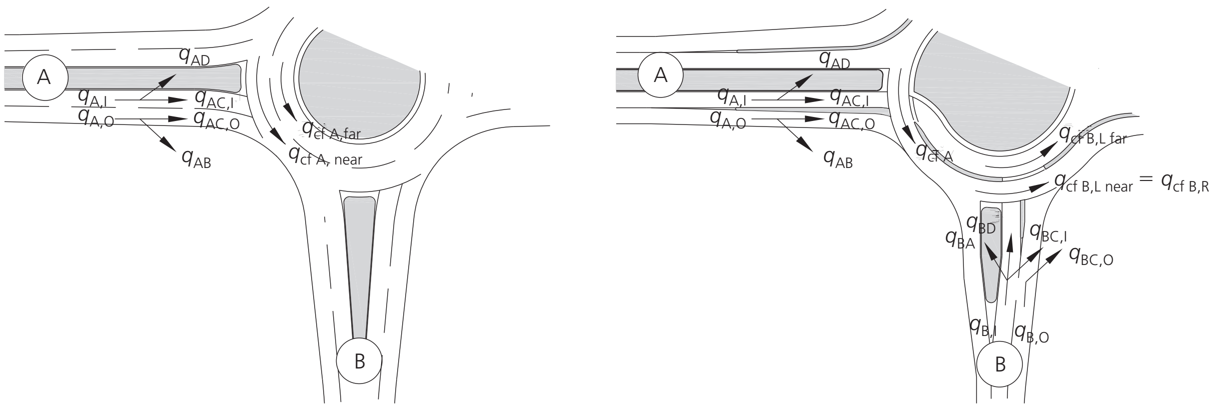

Figure 2. Notation for entry and opposing flows

Single-lane roundabout		Double-lane roundabout			
		Inside entry lane		Outside entry lane	
t_c: s	t_f: s	t_c: s	t_f: s	t_c: s	t_f: s
3·57	2·19	3·06	2·22	2·83	2·26

Table 1. Gap-acceptance parameters estimated from field data

found that traffic in the inner approach lane was affected equally by traffic in both circulating lanes, whereas there were significant differences in the outer lane. When compared with the superimposed case, the critical headway was approximately 10% smaller for the far lane (closest to the central island) and 10% higher for the near lane (closest to the entry). These conversion factors were applied to the double-lane data from Table 1, resulting in the non-superimposed parameters shown in Table 2 for two-lane roundabouts at the near and far lanes.

The value of critical headways for the far lane at the outer entry may seem unrealistic. However, it reflects the fact that many right-turning drivers disregard the corresponding opposing traffic, particularly when they realise that those drivers will continue circulating to take a different exit.

Opposing lane	Inside entry lane		Outside entry lane	
	t_c: s	t_f: s	t_c: s	t_f: s
Far	3·06	2·22	2·55	2·26
Near	3·06	2·22	3·11	2·26

Table 2. Gap-acceptance parameters assigned to normal double-lane roundabouts

In the absence of local data for turbo-roundabouts, the parameters at the different entry lanes were based on the average figures found for Dutch turbo-roundabouts (Fortuijn, 2009b). The figures listed in that study for two-lane roundabouts, where only inner entry data were available ($t_c = 2{\cdot}9$–$3{\cdot}2$ s), are remarkably similar to those listed in Table 2 and so the average parameters from Dutch turbo-roundabouts were used (see Table 3).

3.4 Capacity curves

Replacing the gap-acceptance parameters in Equation 1, the capacity curves (Figures 3 and 4) for the different entry lanes of normal and turbo-roundabouts are obtained. It becomes clear that the differences in the critical headway and follow-up times have a very low impact on capacity (e.g. compare Figures 3(a) and 3(b)) compared with the often-disregarded traffic allocation in the circulatory lanes. This agrees with the results of a sensitivity analysis (Hagring, 1998), which revealed that the allocation of the major flow in different circulatory lanes has a considerable effect on the capacity for an entering minor stream (up to 20% of the geometric capacity), resulting in maximum capacity when the major flow is equally distributed to the circulatory lanes and minimum capacity when all opposing vehicles circulate in the lane with the highest critical and follow-up headways.

4. Results

4.1 Scenario 1: symmetrical demand

For major entry flows of 1000 vehicles/h (Figure 5(d)), a maximum entry flow of 2100 vehicles/h at each minor entry was reached (which should be added to the entry flow at the major entries: 1000 vehicles/h per entry, totalling 6200 vehicles/h for the whole roundabout capacity). As might be expected, this capacity was obtained for the case when there are no left turns and the vehicles are more or less equally split between right-veering and through traffic. The minimum capacity is found when

Opposing lane	Minor direction				Major direction			
	Inside lane		Outside lane		Inside lane		Outer lane	
	t_c: s	t_f: s	t_c: s	t_f: s	t_c: s	t_f: s	t_c: s	t_f: s
Far lane	3·2	2·2	3·9	2·1	3·6	2·2	3·9	2·1
Near lane	3·2	2·2	3·9	2·1	3·6	2·2	3·9	2·1

Table 3. Gap-acceptance parameters assigned to turbo-roundabouts (average figures from Holland)

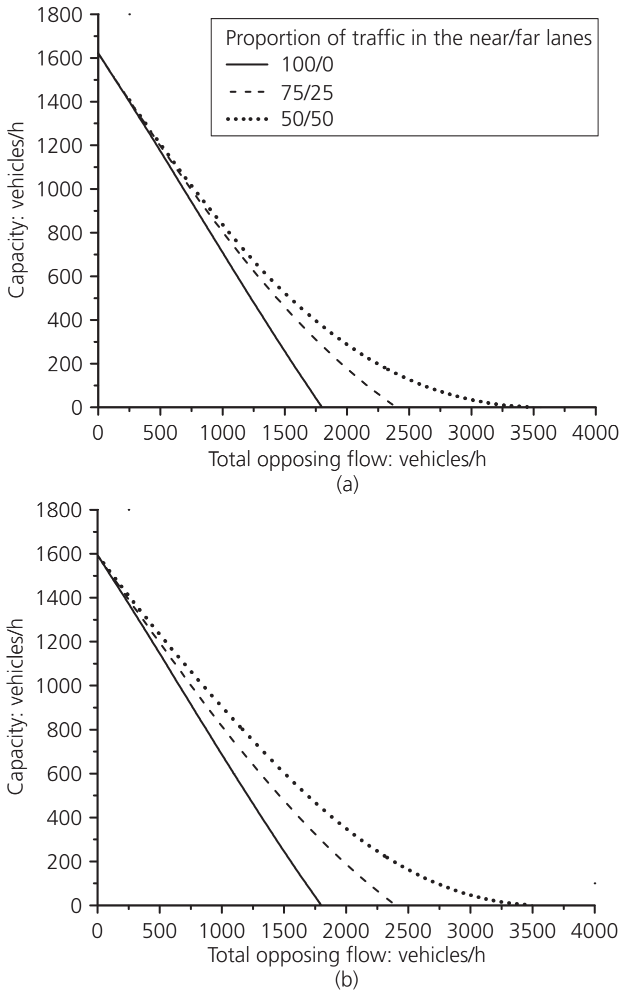

Figure 3. Normal roundabout: capacity against circulatory traffic for different allocations of vehicles in the circulatory lanes (near/far). Major and minor directions: (a) inner lane; (b) outer lane

all minor entry vehicles turn left (570 vehicles/h per minor entry).

At the turbo-roundabout, for major entry flows of 1000 vehicles/h (Figure 5(e)), the maximum flow at the minor roads is slightly higher (2310 vehicles/h when 68% of the entry traffic turns right and the other 32% go through). Again, the minimum flow leading to saturation (580 vehicles/h) occurs when all entry vehicles turn left.

Finally, the comparison between the two layouts (Figure 5(f)) reveals that the turbo-roundabout has a better relative performance when the proportion of right turners is very high (above 60%), with gains of up to 114% in the maximum flow at the minor entries, in relation to that presented by the normal roundabout, for the extreme case when all minor entry drivers turn right. The worst relative performance of the turbo-roundabout happens for the opposite demand distribution (34% left and 66% through), in which case there is a relative reduction of 43% in the maximum flow at the minor entries.

In order to identify the role of the major flow levels in these results, the calculations were repeated for two more demand levels at each of the major entries: low (500 vehicles/h) and high (1500 vehicles/h) (see Figures 5(a)–5(c) and 5(g)–5(i)). As expected, lower maximum entry flows at the minor entries were obtained for the latter case. More interesting, it can be seen that the higher the existing major flow levels, the higher the proportion of right-turning manoeuvres there will have to be for turbo-roundabouts to provide higher capacities than normal roundabouts.

4.2 Scenario 2: anti-symmetrical demand

The maximum capacity of the normal roundabout under anti-symmetrical demand in the minor entries is obtained when the proportion of left and right traffic at each entry is the same, regardless of the proportion of through traffic (see Figure 6(d)). The optimal split for minor entries is: left, 18%; through, 64%; right, 18% (1650 vehicles/h at each of the minor entries). The minimum capacity (650 vehicles/h at each minor entry) is obtained when through traffic is null and all minor entry vehicles take the same direction on the major road.

The maximum capacity on the turbo-roundabout (Figure 6(e)) is lower than a normal roundabout, and is also obtained for equal proportions of left and right traffic but for a null proportion of through traffic (1150 vehicles/h).

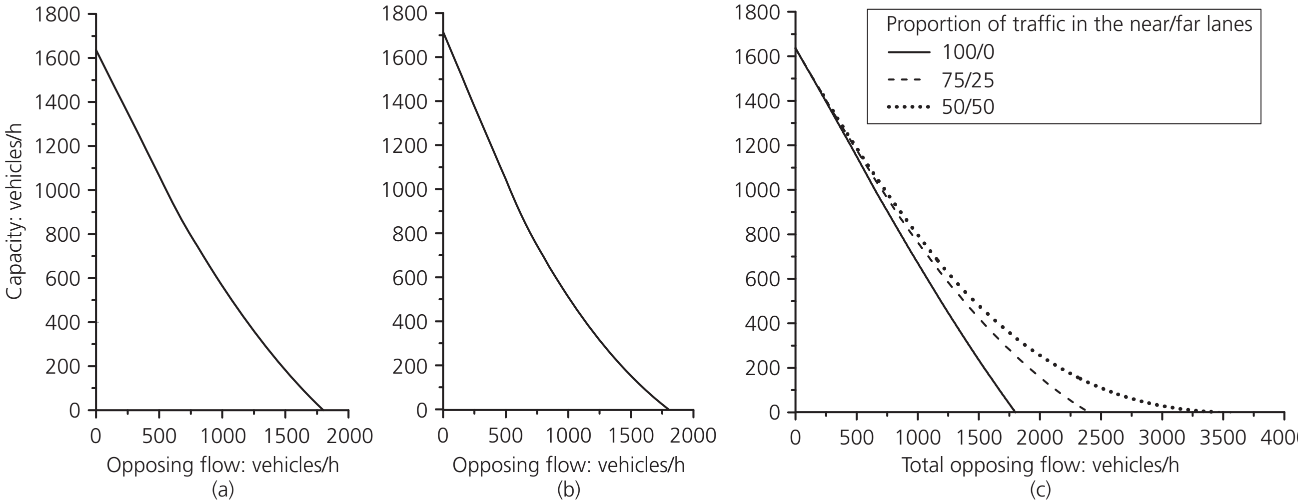

Figure 4. Turbo-roundabout: capacity against circulatory traffic for different allocations of vehicles in the circulatory lanes (near/far). (a) Major direction; inner lane. (b) Major and minor directions; outer lane. (c) Minor direction; inner lane

The comparison of capacities under the two layouts (Figure 6(f)) reveals that the turbo-roundabout performs slightly better than the normal one when the proportion of through traffic is very low, with gains below 20% in the secondary direction. The worst relative performance of the turbo-roundabout is obtained when all minor entry drivers go through, in which case there is a 42% reduction in relation to the normal roundabout.

The impact of major flow levels on the minor entry capacity is similar to the symmetrical demand case (Figures 5(a)–5(c) and 5(g)–5(i)): higher flows in the major direction lead to higher optimal proportions of right- or left-turning traffic, and to a general lower relative performance of turbo-roundabouts. In fact, for very high demand levels in the main direction (above 2000 vehicles/h), the normal roundabout offers higher capacity than the turbo, regardless of the directional split at the minor entries.

4.3 Expected results in real roundabouts

In order to assess the operational differences under real, common, split-demand situations, data were collected at ten roundabouts, mostly in the city of Viseu, Portugal, during the morning rush hour (8·00–9·00 a.m.) (see Table 4). The volumes were obtained from manual counts and the proportions were obtained by visual tracking of random vehicles at each entry (approximately 150 vehicles per entry). Most of these roundabouts are on an urban ring road and are optimised for capacity with flared entries or slip lanes.

Analysis of the entry proportions indicates that these roundabouts are operating under typical conditions, as follows.

- Unequal distribution of traffic among entries, with a clear distinction between major and minor directions (identified in Table 4 as A or C and B or D entries respectively).
- In the major direction, the through movement is usually much more important than in the minor direction (average respective proportions of 62% and 34% of the corresponding total entry flow).
- Usually, demand for the right turn and for the left and U-turns combined is similar.
- U-turn movements are of little significance.

For comparison purposes, the capacities were calculated assuming the reference layouts defined earlier. Taking the Paulo VI roundabout as an example, at major entry A (hospital), the concentration of opposing traffic in a single lane raises the saturation ratio from 49·8% to 79%. At minor entry B (Centro), the proportion of right turners is very low (19%), which leads to wasted capacity at the right lane and unequal saturation ratios at the left and right entry lanes (76% and 16%). The normal roundabout allows distribution of the through traffic, resulting in equal (and lower) saturation ratios (43·4% for both lanes).

The results clearly show that the turbo-roundabout layout, under typical traffic distributions and for the reasons already stated in Section 3, is no match for the normal roundabout from the capacity point of view. The capacity of the major entries is always higher on the normal roundabouts, with differences of up to 67% (roundabout Fonte Luminosa, entry A). Regarding the minor entries, while at most normal roundabouts the capacity ratios are equal for both lanes of a given entry, the turbo-

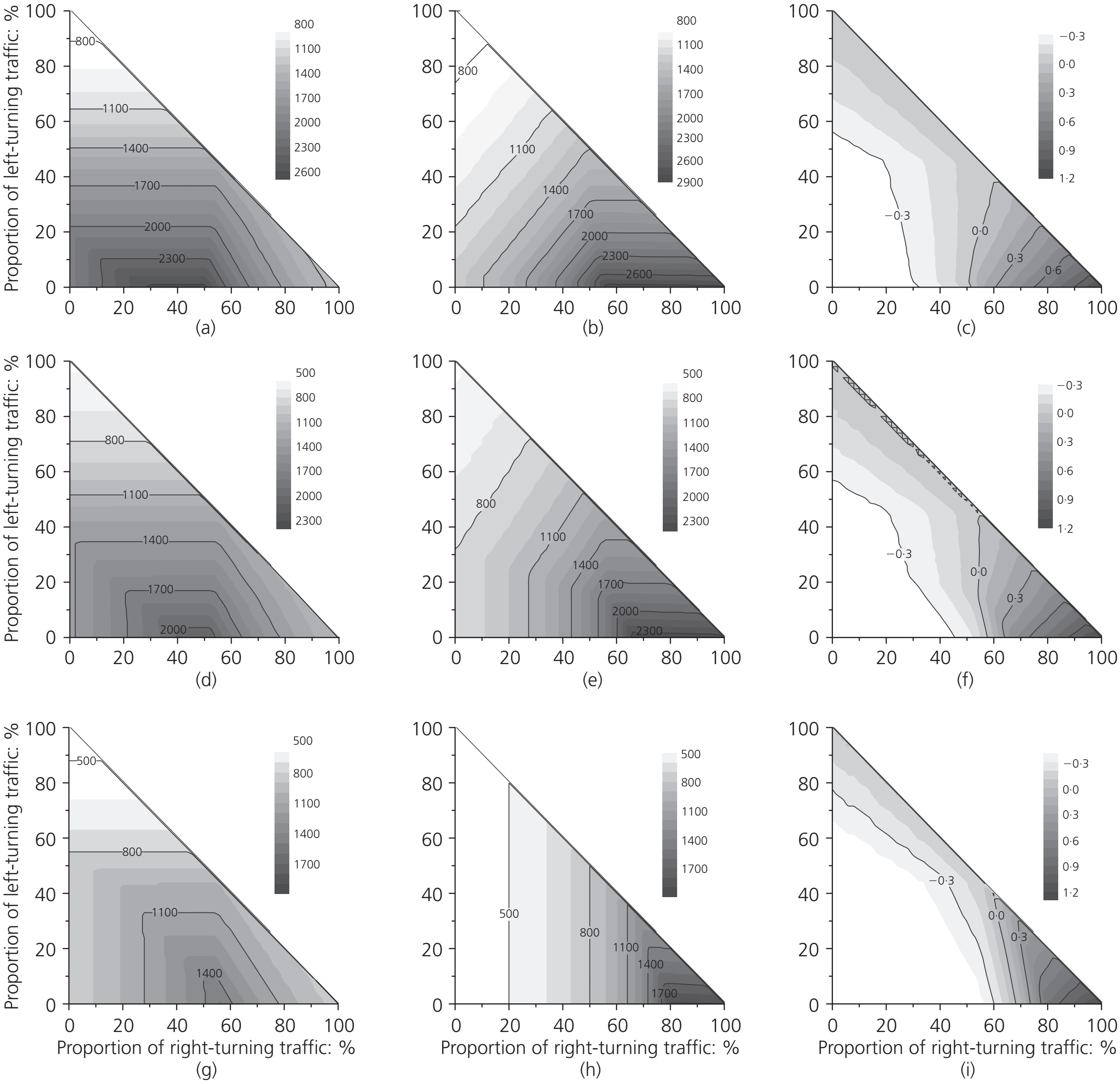

Figure 5. Maximum demand flow at minor entries under symmetrical demand. Left-hand plots, normal roundabout; centre, turbo-roundabout; right, relative difference $((C_{turbo} - C_{normal})/C_{normal})$. (a)–(c), $q_A = q_C = 500$ vehicles/h; (d)–(f), $q_A = q_C = 1000$ vehicles/h; (g)–(i), $q_A = q_C = 1500$ vehicles/h

roundabout layout leads to unequal saturation levels, with differences that can be up to 82% (roundabout Palácio Gelo, entry B).

5. Conclusion

The iterative capacity calculation procedure presented in this paper, based on gap-acceptance theory, allows accurate capacity estimations of normal and turbo-roundabouts. The capacity of these two layouts was compared for a wide range of demand scenarios, using synthetic data, leading to the following conclusions.

- Capacities at the major entries of a turbo-roundabout are always lower than for normal roundabouts because opposing

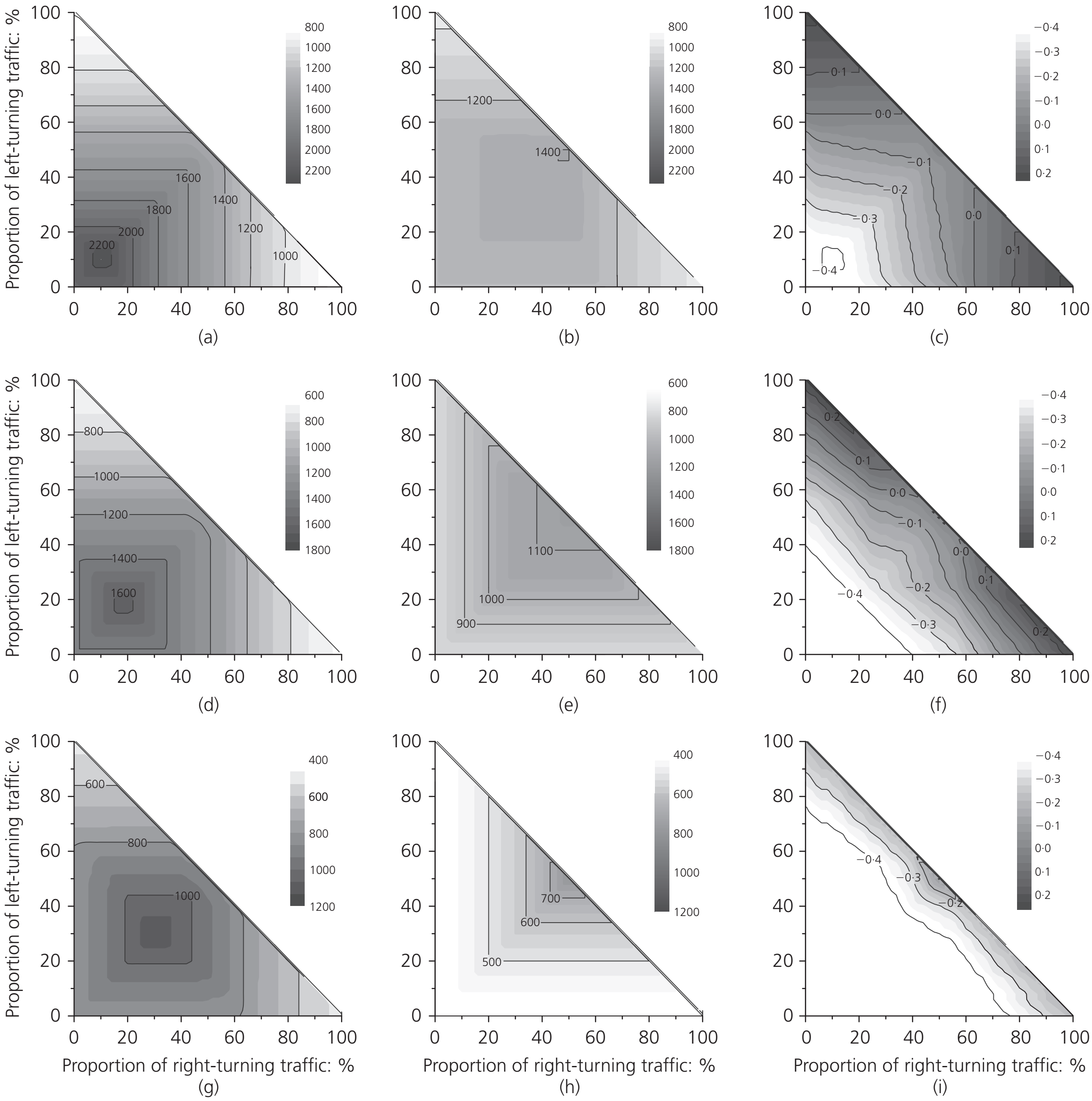

Figure 6. Maximum demand flow at minor entries under anti-symmetrical demand. Left-hand plots, normal roundabout; centre, turbo-roundabout; right, relative difference $((C_{turbo} - C_{normal})/C_{normal})$. (a)–(c), $q_A = q_C = 500$ vehicles/h; (d)–(f), $q_A = q_C = 1000$ vehicles/h; (g)–(i), $q_A = q_C = 1500$ vehicles/h

traffic is concentrated in a single lane (the effect is more significant when traffic is evenly distributed in the major lanes of a normal roundabout).

- The relative performance of the turbo-roundabout worsens with increasing demand levels in the major direction.
- At the minor entries, the turbo-roundabout performs better only under very specific demand scenarios, specifically when the proportion of right-turning traffic is very high. That proportion depends on the demand levels in the major direction and is usually above 60%.

Roundabout	Entry		No. of lanes[a]	Demand q: vehicles/h	Entry proportions: %				Capacity ratio ($x = q/C$): %[b]			
									Normal roundabout		Turbo-roundabout	
					U-turn	Left	Through	Right	Left	Right	Left	Right
Paulo VI	A	Hospital	2	882	1	12	62	25	49·8	49·8	79	79
4276 vehicles/h	B	Centro	2/3	526	0	32	49	19	43·4	43·4	76	16
	C	Montebelo	2	1718	0	4	53	44	71·5	71·5	85	85
	D	Coimbra	2/3	1150	3	56	20	20	104·6	58·0	138	17
Nelas	A	Hospital	2	731	0	46	51	3	49	49	91	91
4246 vehicles/h	B	Centro	2	453	0	18	61	21	31	31	57	15
	C	Mac	2	1459	2	8	30	61	55	78	66	110
	D	Nelas	2	1603	0	32	32	36	72	72	100	35
Sátão	A	Santiago	2	734	3	17	68	12	42	42	71	71
2979 vehicles/h	B	Centro	1	149	0	19	43	39	11	11	16	9
	C	R. Fontelo	2	866	0	5	41	53	28	32	29	33
	D	Sátão	2	1230	0	52	28	20	52	45	80	15
Palácio Gelo	A	Nelas	2	1299	2	16	67	16	53	53	62	62
3806 vehicles/h	B	Hospital	2 + 1	685	0	38	52	10	43	43	88	6
	C	Centro	2	1360	4	17	72	7	69	69	100	100
	D	Repeses	2 + 1	462	2	7	38	53	42	42	46	36
Montebelo	A	Rot. Marzovelos	2/3	1122	0	6	68	27	43	43	47	47
3417 vehicles/h	B	Centro	2	375	4	33	23	40	20	20	27	12
	C	Rot. C. Lopes	2/3	1328	1	8	83	8	48	48	50	50
	D	Montebelo	2	592	0	18	30	53	45	45	50	39
Carlos Lopes	A	Montebelo	2/3	1038	0	23	73	5	45	45	55	55
3555 vehicles/h	B	Centro	2/3	390	2	30	39	30	26	26	41	14
	C	Rot. Telecom	2/3	1047	0	8	71	21	43	43	50	50
	D	Vildemoinhos	2	1080	0	20	28	53	59	59	61	50
Mangualde	A	Rb. Fontelo	2	1015	1	37	54	8	44	44	54	54
3091 vehicles/h	B	Centro	1/2	232	0	25	59	15	15	15	29	4
	C	Un. Católica	2	1046	1	6	74	19	45	45	54	54
	D	Mangualde	1/2	798	3	27	35	35	42	42	61	23
Continente	A	Centro	2 + 1	840	0	7	73	20	28	28	28	28
2432 vehicles/h	B	Continente	2	327	0	66	26	9	20	10	29	2
	C	Abraveses	2	1040	1	5	94	0	39	39	42	42
	D	Sto. Estevão	1	225	0	7	40	53	16	16	17	16
Fonte Luminosa	A	Telecom	2/3	864	5	52	36	7	86	52	139	119
3622 vehicles/h	B	Centro	1/2	346	7	19	43	31	25	25	38	14
	C	Cava Viriato	3	788	4	33	43	20	37	37	50	50
	D	Av. Europa	3	1624	1	26	33	40	76	76	96	50
Estação Velha	A	Casa do Sal	2	571	8	42	28	22	23	22	25	25
(Coimbra)	B	Eiras	1/2	603	5	58	35	2	33	19	53	1
2745 vehicles/h	C	Loreto	1	790	2	6	83	9	41	41	60	60
	D	Figueira	1 + 1	781	0	18	32	50	48	48	54	48

[a] $a/b = a$ lanes in the approach $/b$ lanes in entry; $a + 1 = a$ lanes in the entry plus one slip lane for right turns
[b] Assuming all roundabouts have the layouts defined in Section 3 (see Figure 1)

Table 4. Comparison of roundabout capacities under real demand flows

- The traffic data collected at Portuguese roundabouts suggest that the abovementioned demand scenarios are relatively uncommon in real-world applications.

In brief, under most demand scenarios, a two-lane roundabout provides more capacity than the equivalent turbo-roundabout. However, this does not diminish the usefulness of turbo-roundabouts. Most conventional roundabouts currently operate far below capacity and most would still do so if they were converted. In addition, their improved operational safety is widely recognised, which makes them a true alternative to other unsignalled intersections.

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