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Performance Analysis of Basic Turbo-Roundabouts in Urban Context

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Abstract

A turbo roundabout is a new type of canalized multilane intersection in which the physical separation between lanes helps to prevent side collisions when crossing the roundabout. This paper presents an estimation of capacity, delays and level of service of basic turbo roundabouts in undersaturation conditions, considering both vehicle flow and pedestrian traffic. The traffic performance model was developed by evaluating the capacity for each entry lane. Owing to the geometric features of the intersection, the total entry capacity is obtained by considering different values of the pedestrian impedance factor and degree of saturation at both the right-turn and left-turn lanes.

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Keyword: Turbo roundabouts, pedestrians, capacity, delay, level of service

1. Introduction

The ever-increasing mobility demand for private transport often makes it highly critical to circulate in urban and suburban contexts. The deterioration of levels of service and the increase of other negative externalities from the private transport (among which the air pollutant emissions) are firstly caused by the unbalanced interaction between supply and demand (or in other words, in nonequilibrium conditions), the latter consisting of road infrastructures with geometric and functional standards by now unsuitable for the high traffic flows there in transit. Especially under interrupted flow conditions, typical of urban roads or the suburban road network where they are extremely close to one another, intersections play an essential role on condition that their geometric scheme, dimensions and type of regulations are carefully chosen.

Such choices actually give rise to effects differing according to the local traffic intensity and mode. In the latest years the scientific research in the field of road infrastructures has been directed to design new types of road

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intersections, with the view to increasing their capacity and improving their safety conditions. Among the most interesting solutions, there are schemes similar to traditional roundabouts, even if characterized by somewhat diverse operational modes. More specifically, they are *spiral roundabouts*, *turbo roundabouts* and *flower roundabouts* whose individual capacity and safety peculiarities allow them to be implemented more and more frequently in Europe (especially in Holland, Slovenia and Germany) in order to redevelop the black spots of the road network or to improve the performances of the intersections already in operation.

Compared to conventional schemes, marked differences can especially be noticed in turbo- and flower roundabouts whose configuration of the central island and ring lane - as well as physical separation of the lanes (in the case of turbo roundabout) - allow potentially higher safety conditions than those obtainable from conventional geometric schemes, and even higher capacity values in specific traffic conditions.

Moreover, the conversion of a conventional intersection already in operation or a roundabout into a turbo roundabout can determine high benefits for the safety of users, (especially pedestrians and cyclists) against a modest financial investment, thanks to the small number of conflict points between vehicular trajectories and to the reduced running speed on the ring [1, 2, 3].

This paper has the following main objectives:

- To examine design standards for the geometry of turbo roundabouts;
- To suggest a theoretical and experimental model for the capacity estimation which involves the various traffic elements of an urban context, especially the pedestrian flow if this takes priority over the vehicle flow.

2. Geometry of turbo roundabouts

Turbo roundabouts are a particular roundabout intersection type where lanes are bounded by both road markings and curbs installed in legs and ring lane, thus specifying the lanes at entry and devoting them only to predetermined turning manoeuvres. From the operational profile, unlike the conventional roundabouts - where vehicles reach the give-way line and only afterwards they set the trajectory to exit from one of the intersection legs - in turbo roundabouts users are forced to preselect the correct lane even at dozens of meters before they enter the ring, just as a result of the physical separation of the lanes [4, 5, 6, 7, 8].

Compared to conventional schemes, the main advantages of a turbo roundabout are:

- limited number of potential conflict points among vehicular trajectories;
- slower speed along the ring;
- low risk of side-by side accidents.

It follows that turbo roundabouts can appropriately replace conventional *double-lane* roundabouts when a higher safety level at intersections has to be guaranteed, e.g. in constant pedestrian and two-wheel traffic, as pointed out by Fortuijn [9]. On the other hand, compared to conventional roundabouts, turbo roundabouts have such various disadvantages as:

- presence of through conflict points in left-turning maneuvers (see Fig. 1);
- higher values of the critical gaps in through and left-turning maneuvers;
- generally lower capacity than conventional *double lane* roundabouts.

Also in light of the abovementioned considerations, turbo roundabouts clearly show higher and higher functional capacities than *single lane* roundabouts but generally inferior to *double lane* roundabouts. On the other hand, compared to the latter, they guarantee a more effective speed control and a smaller number of conflict points.

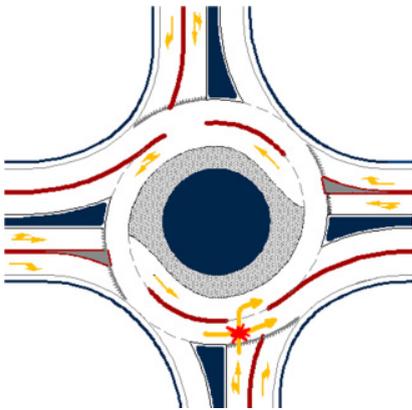


Fig. 1. Basic Turbo roundabout (crossing conflict point at the entry)

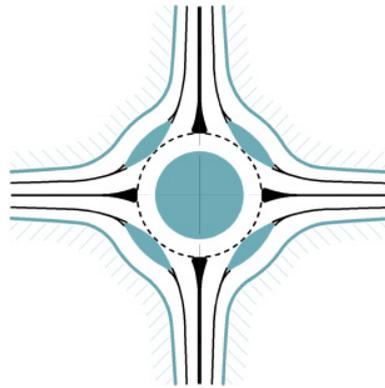


Fig. 2a. Flower roundabout (roundabout with "depressed" lanes for right-turners)



Fig. 2b. Double-Lane Roundabout

With the aim of exploiting the benefits of turbo roundabouts and solving the problem of through conflict points, flower roundabouts have recently been designed [10, 11, 12, 13] ; their geometric scheme is illustrated in Figure 2a.

The operation and geometry of these intersections are rather different from conventional roundabouts and also from turbo roundabouts, so they should be dealt with separately. Therefore, the observations in this paper are confined to turbo roundabouts and cannot be applied to flower roundabouts. Essential geometric characteristics. The turbo-shaped central island is obtained from arcs of circumferences with different centre and radius or from Archimedean spiral [8].

The values of radii of curvature at the central island should be selected so as to guarantee lower running speeds along the roundabout or equal to 40 km/h [8].

The values of entry and exit radii do not substantially differ from those set in traditional roundabouts [8]: minimum entry radius, $R_{e,min} = 12.00$ m; minimum exit radius, $R_{u,min} = 15.00$ m.

Moreover, in order to help heavy vehicles to perform entry and exit manoeuvres at a roundabout, the minimum width should be 4.50 m for exit lanes and 4.00 m for entry lanes [14, 15, 16].

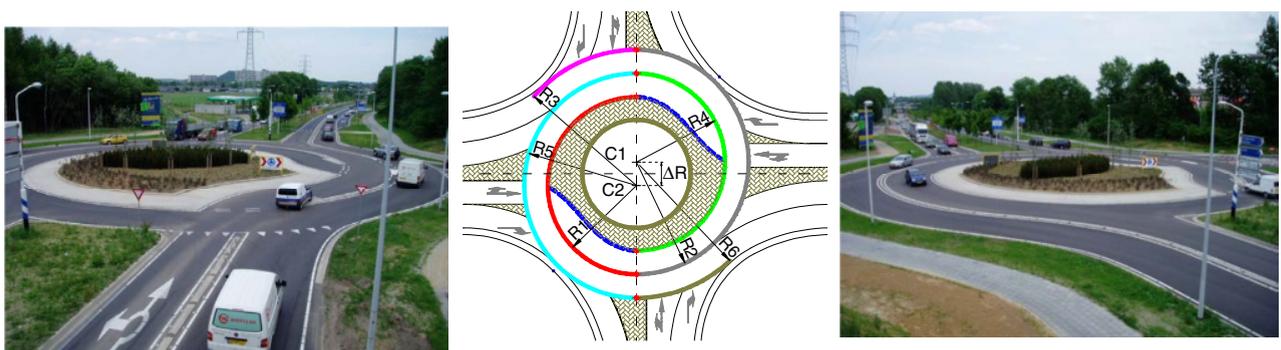


Fig. 3. Layout and photo of Basic turbo roundabouts

3. Capacity estimation of turbo roundabouts in urban contexts

The geometric characteristics of turbo roundabouts and the separation of ring lanes and entry legs require the capacity estimation of each lane [7, 8].

Such a methodological approach has recently been introduced in *Highway Capacity Manual* [17] and in *Roundabouts: An Informational Guide - Second Edition* [18] for conventional roundabouts, since the lane demand and consequently saturation degrees appear to be generally unbalanced.

As roundabouts are more appropriate in urban contexts, the capacity analysis here suggested takes into account the different traffic components allowed to circulate in urban contexts, especially pedestrians. As a matter of fact, pedestrian crossings, located at legs near roundabout entries, can significantly influence the roundabout capacity owing to the priority given to pedestrian flows.

The flowchart in Figure 4 illustrates how to calculate the performances of turbo roundabouts. It is noteworthy to observe that roundabout entry lane capacity can be evaluated through various methods already implemented worldwide, among which the following have been taken into consideration in this research:

A. *Right-turn lane:*

- Tanner equation (adjusted by Brilon-Wu);
- NCHRP Report 672 Method

B. *Through and left-turn lane*

- Harders Model
- NCHRP Report 672 Method

The analytical expressions are reported below. It has been noted that the formulation of NCHRP Report 672 [18] model applied to both entry lanes overestimates the capacity whenever the circulating flow is very heavy.

For instance, when the circulating flow is $q_K = 2,000$ veh/h, the resulting inner entry lane capacity is equal to $C_{E,TLT} = 252$ veh/h; when the circulating flow is $q_K = 2,500$ veh/h, it is equal to $C_{E,TLT} = 173$ veh/h and with $q_K = 3,000$ veh/h, it is equal to $C_{E,TLT} = 119$ veh/h.

On the other hand, experimental surveys [2, 19] have shown that the ring capacity does not exceed 1,600 veh/h in compact roundabouts with 2 ring lanes or 2,500 veh/h in large roundabouts (*see* Table 1). The entry capacity corresponding to such circulating flow values is obviously near zero.

Table 1. Estimation of ring capacity in various roundabout types

| Roundabout types | No. of entry lanes | Ring capacity [veh/h] |
|--|--------------------|-----------------------|
| Roundabouts with 1 ring lane (mini- and compact roundabouts) | 1 | 1600 |
| Compact roundabouts with 2 ring lanes | 1 | 1600 |
| | 2 | 1600 |
| Large roundabouts | 1 | 2000 |
| | 2 | 2500 |

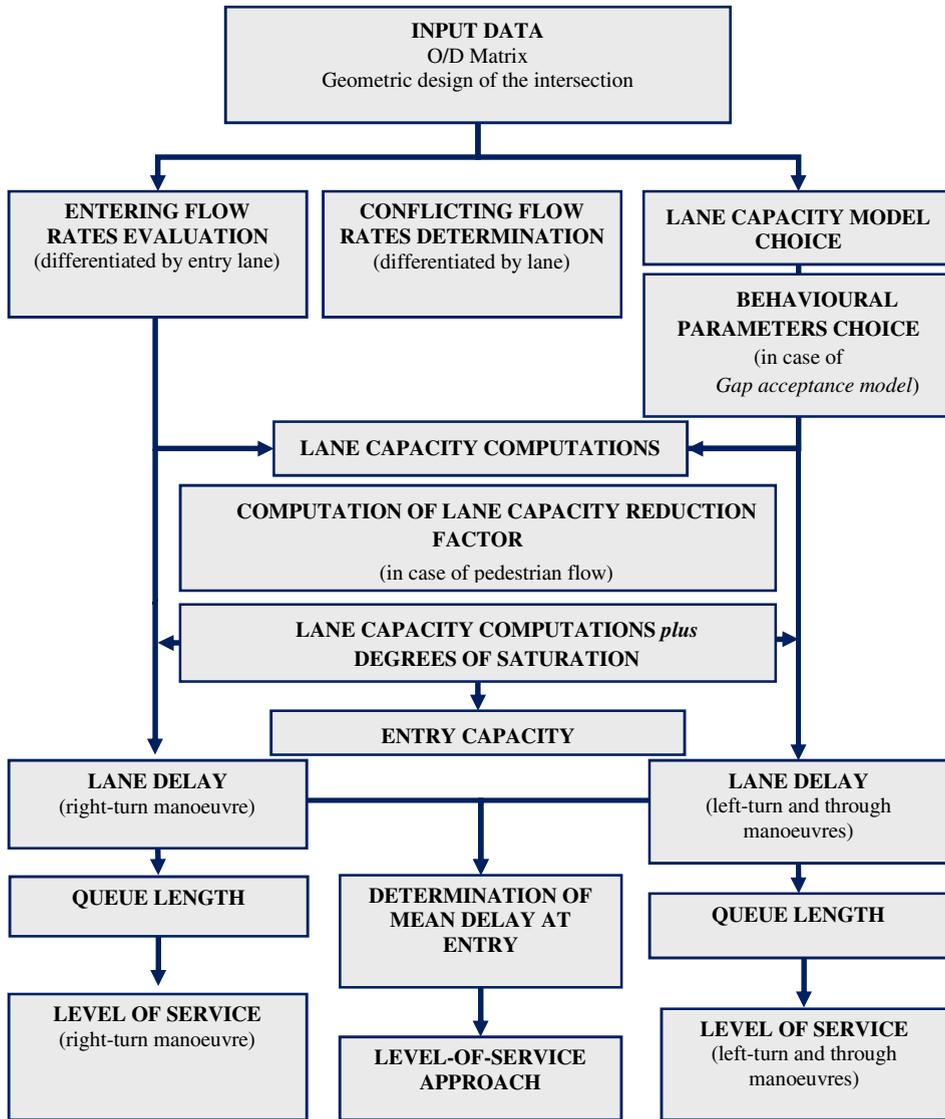


Fig. 4. Functional analysis flowchart for basic turbo-roundabouts

3.1. Right-Turn Lane Capacity

In order to evaluate the right-turn lane capacity, Tanner equation [21] as modified by Brilon [22], and the formulation introduced in *Roundabouts: An Informational Guide - Second Edition* [18] resuming HCM 2010 method [17], have been taken into consideration.

a) *Tanner equation* - Tanner equation, as modified by Brilon, is reported below:

$$C_{E,R} = 3600 \cdot \left(1 - \frac{T_{\min} \cdot q_K}{n_K \cdot 3600}\right)^{n_K} \cdot \frac{n_Z}{T_f} \cdot e^{-\frac{q_K}{3600} \cdot \left(T_g - \frac{T_f}{2} - T_{\min}\right)} \tag{1}$$

where: $C_{E,R}$ = capacity of the right-turn lane at the entry E [veh/h]; q_K = circulating vehicles close to the entry E, just next to the right-turn lane R [veh/h]; n_K = number of ring lanes; n_Z = number of entry lanes; T_g = critical gap [s]; T_f = follow – up time [s]; T_{\min} = the least headway between vehicles moving along the ring lanes [s].

The equivalence coefficients can reasonably assume the following values: 1 heavy vehicle = 1,5 ÷ 2 cars (depending on the type of heavy vehicle); 1 bicycle/motorbike = 0,5 cars. As suggested by Brilon et al. [23] in case of traditional roundabout, the following values can be assumed for the behavioural parameter: $T_g = 4,1$ s, $T_f = 2,9$ s, $T_{\min} = 2,1$ s. Experimental measurements carried out in three sites by Fortujin [5] have shown that the critical gap in right-turn lanes on the main road (major leg) of basic turbo roundabouts assumes inferior values to those provided by Brilon: $T_g = 3.28 \pm 0.23$ (n = 115); $T_g = 3.35 \pm 0.32$ (n= 424); $T_g = 3.55 \pm 0.48$ (n = 280). On the other hand, T_f and T_{\min} assume similar values to those in traditional roundabouts.

Introducing the values $n_K = 1$ and $n_Z = 1$ (i.e. entering vehicles from right-turn lane only interfere with circulating vehicles moving along one lane) in the previous equation, the capacity relation for the examined lane can be immediately obtained:

$$C_{E,R} = 3600 \cdot \left(1 - \frac{T_{\min} \cdot q_K}{3600}\right) \cdot \frac{1}{T_f} \cdot e^{-\frac{q_K}{3600} \cdot \left(T_g - \frac{T_f}{2} - T_{\min}\right)} \tag{2}$$

The previous equation highlights that the right-turn capacity is influenced by circulating vehicles on the external one lane ($q_K = Q_{c,e}$) and by user behaviours (through parameters T_g , T_f , T_{\min}).

b) *NCHRP Report 672 Model* – The lane capacity can be obtained by the following equation:

$$C_{E,R} = 1130 \cdot e^{(-0.7 \cdot 10^{-3}) \cdot q_{k,pce}} \tag{3}$$

$$q_{k,pce} = \frac{q_k}{f_{HV}} \tag{4}$$

$$f_{HV} = \frac{1}{1 + P_T \cdot (E_T - 1)} \tag{5}$$

where: $C_{E,R}$ = capacity of the right-turn lane at the entry E [pc/h]; $q_{k,pce}$ = circulating vehicles close to the entry E, just next to the right-turn lane R [pc/h]; $q_{k,pce}$ = circulating flow rate [pc/h]; q_k = circulating flow [veh/h]; f_{HV} = heavy vehicle adjustment factor; P_T = proportion of demand volume that consists of heavy vehicles E_T = passenger car equivalent for heavy vehicles.

The equivalence coefficients E_T are equal to 1.0 for Passenger cars, 2.0 for Heavy Vehicles and 0,5 for Bicycles

3.2. The Capacity At Through And Left-Turn Lane

- a) *Harders Model* - Considering the operational conditions described above (see Fig. 1), at through and left-turn lanes the capacity can be computed schematizing the manoeuvring area as a TWSC intersection [7, 17], where circulating vehicles have priority. Harders model [24] can be applied to evaluate the capacity lane. Let it be:

$$C_{E,TLT} = q_k \cdot \frac{e^{-q_k \cdot \frac{T_{g,x}}{3600}}}{1 - e^{-q_k \cdot \frac{T_{f,x}}{3600}}} \quad (6)$$

with: $C_{E,TLT}$, capacity of through and left-turn lanes; q_k , conflicting flow rate; $T_{g,x}$ and $T_{f,x}$ critical gap and the follow-up-time respectively; $q_k = Q_{c,e} + Q_{c,i}$; $Q_{c,e}$ = circulating flow on the exterior ring lane; $Q_{c,i}$ = circulating flow on the inner ring lane.

The critical gap ($T_{g,x}$) and the follow-up-time ($T_{f,x}$) can be assumed as: $T_g = 6,4$ s; $T_f = 3,5$ s.

- b) *NCHRP Report 672 Model* – The lane capacity is determined with the following equation:

$$C_{E,TLT} = 1130 \cdot e^{(-0.75 \cdot 10^{-3}) \cdot q_{k,pce}} \quad (7)$$

where: $q_{k,pce}$ = circulating vehicles close to the entry E, just next to through and left-turn lanes [pc/h], to be computed by means of relation (4); $q_k = Q_{c,e} + Q_{c,i}$ = circulating flow [veh/h]; f_{HV} = heavy vehicle adjustment factor, to be computed by means of relation (5); P_T = proportion of demand volume that consists of heavy vehicles E_T = passenger car equivalent for heavy vehicles.

Figure 5 illustrates a comparison between entry lane capacities and the models described above. As observed in *NCHRP – Report 672 model*, entry lane capacities are not annulled by high circulating flows, that is over 2,000 veh/h, which occurs, instead, by using Tanner and Harders models. This is the reason why the following numerical formulations and graphical representations refer to Tanner model (for the right-turn lane) and Harders model (for through and right-turn lanes).

3.3. Effect Of Pedestrians On Traffic Flow

The effect of pedestrians on traffic flow is always observed in urban areas where pedestrians have the right of way over entry vehicles. Even though there are no experimental data specifically referred to turbo roundabouts, the effect of pedestrian flow on the lane capacity can be assessed by means of German method [25]. The model includes the determination of a capacity reduction factor M. For a single lane entry the reduction factor M is as follows:

$$M = \frac{1119,5 - 0,715 \cdot q_k - 0,644 \cdot Q_{ped} + 0,00073 \cdot q_k \cdot Q_{ped}}{1069 - 0,65 \cdot q_k} \quad (8)$$

where: q_k = conflicting flow rate (pcu/h); Q_{ped} = pedestrian flow (ped/h).

If we elaborate the case under study, it follows:

$$M_{E,R} = (1119,5 - 0,715 \cdot Q_{c,e} - 0,644 \cdot Q_{ped} + 0,00073 \cdot Q_{c,e} \cdot Q_{ped}) / (1069 - 0,65 \cdot Q) \tag{9}$$

$$M_{E,TLT} = [1119,5 - 0,715 \cdot (Q_{c,e} + Q_{c,i}) - 0,644 \cdot Q_{ped} + 0,00073 \cdot (Q_{c,e} + Q_{c,i}) \cdot Q_{ped}] / [1069 - 0,65 \cdot (Q_{c,e} + Q_{c,i})] \tag{10}$$

$$C_{E,R}^{ped} = C_{E,R} \cdot M_{E,R} \tag{11}$$

$$C_{E,TLT}^{ped} = C_{E,TLT} \cdot M_{E,TLT} \tag{12}$$

where: $M_{E,R}^{ped}$ = right-turn lane pedestrian capacity reduction factor; $M_{E,TLT}^{ped}$ = through and left-turn lane pedestrian capacity reduction factor; $C_{E,R}^{ped}$ = right-turn lane vehicle capacity considering impact of pedestrians [veh/h]; $C_{E,TLT}^{ped}$ = through and left-turn lane vehicle capacity considering impact of pedestrians [veh/h]; $C_{E,R}$ = right-turn lane vehicle capacity (no pedestrian crossings, only vehicles) [veh/h]; $C_{E,TLT}$ = through and left-turn lane vehicle capacity (no pedestrian crossings, only vehicles) [veh/h]; C_E^{ped} = entry capacity considering impact of pedestrians [veh/h].

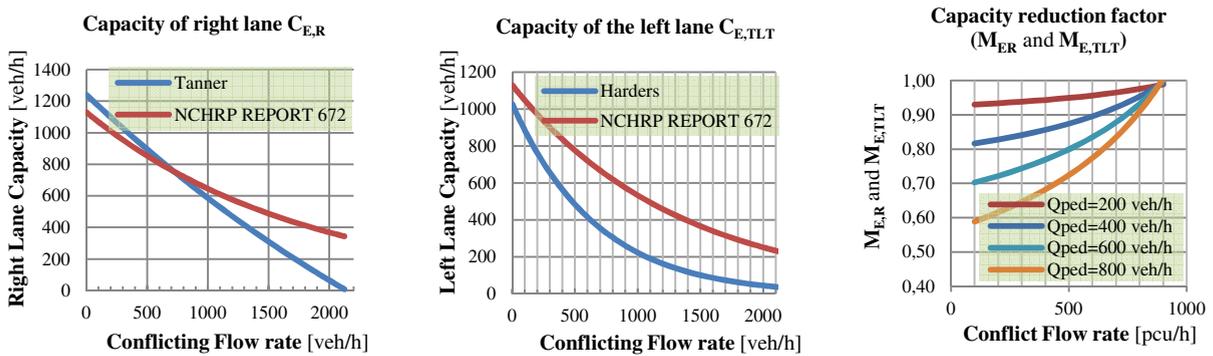


Fig. 5. Comparison between capacity models for entry lanes and values of capacity reduction factor

4. Entry Capacity

Each entry lane at a turbo roundabout is characterized not only by different capacity values (C_i), but also by a different flow rate (Q_i); it results that the degree of saturation ($x_i = Q_i/C_i$) can differ between lanes of the same entry and the total entry capacity is not a simple sum of the single lane capacities. For these reasons the effective entry capacity C_E^{ped} can be obtained from the following equations [8, 12]:

$$C_E^{ped} = \frac{(Q_{E,R} + Q_{E,TLT})}{\max\left[\frac{Q_{E,R}}{C_{E,R}^{ped}}, \frac{Q_{E,TLT}}{C_{E,TLT}^{ped}}\right]} \tag{13}$$

The previous equation shows that each entry capacity arises from the capacity of the single lanes and therefore from: i) conflicting flow; ii) combination of circulating flows at the ring lane; iii) user behaviour (through

parameters T_g, T_f, T_{min}); iv) balance of traffic demand at entry legs; v) pedestrian flow. The maximum entry capacity value is reached only when all the lane utilization ratios are equal to 1 [2, 8]. Therefore, it results that:

$$C_E^{ped} = C_{E,R}^{ped} + C_{E,TLT}^{ped} \tag{14}$$

Only in this condition the entry capacity can be obtained as the sum of the single capacities at entry lanes. Otherwise, where the degrees of saturation $x_{E,R}$ (at a right-turn lane) and $x_{E,TLT}$ (at through and left-turn lanes) are different from each other, the entry capacity assumes a lower value than the sum of the single lane capacities [26] - see the numerical example reported in Table 2.

Table 2. Entry capacity

| ENTRY CAPACITY ESTIMATION | Equal degree of saturation (x) | | | Unequal degree of saturation (x) | | |
|---------------------------|---|---|--|---|---|--|
| | Lane 1  | Lane 2  | Entry  | Lane 1  | Lane 2  | Entry  |
| Volume Q [veh/h] | 500 | 500 | 1000 | 500 | 750 | 1250 |
| Capacity C [veh/h] | 1000 | 1000 | 2000 | 1000 | 1000 | 1667 |
| Degree of saturation x | 0,5 | 0,5 | 0,5 | 0,5 | 0,75 | 0,75 |

5. Evaluation of Delays and Level of Service

After computing the capacity and the degree of saturation of each lane (in case of lane undersaturation and pedestrian flow), it is possible to determine the average control delay [17, 27] of each vehicle at the lane under examination, by means of the following equations [8, 17, 18]:

$$D_{E,TLT}^{ped} = \frac{3600}{C_{E,TLT}^{ped}} + 900 \cdot T \cdot \left[\frac{Q_{E,TLT}}{C_{E,TLT}^{ped}} - 1 + \sqrt{\left(\frac{Q_{E,TLT}}{C_{E,TLT}^{ped}} - 1\right)^2 + \frac{\left(\frac{3600}{C_{E,TLT}^{ped}}\right) \cdot \left(\frac{Q_{E,TLT}}{C_{E,TLT}^{ped}}\right)}{450 \cdot T}} \right] + 5 \cdot \min\left[\frac{Q_{E,TLT}}{C_{E,TLT}^{ped}}, 1\right] \tag{15}$$

$$D_{E,R}^{ped} = \frac{3600}{C_{E,R}^{ped}} + 900 \cdot T \cdot \left[\frac{Q_{E,R}}{C_{E,R}^{ped}} - 1 + \sqrt{\left(\frac{Q_{E,R}}{C_{E,R}^{ped}} - 1\right)^2 + \frac{\left(\frac{3600}{C_{E,R}^{ped}}\right) \cdot \left(\frac{Q_{E,R}}{C_{E,R}^{ped}}\right)}{450 \cdot T}} \right] + 5 \cdot \min\left[\frac{Q_{E,R}}{C_{E,R}^{ped}}, 1\right] \tag{16}$$

where: $D_{E,R}^{ped}$ = average control delay for the right-turn lane [s/veh]; $D_{E,TLT}^{ped}$ = average control delay for through and left-turn lanes [s/veh]; T = reference time (h), (T = 1 for a 1-h analysis, T = 0.25 for a 15-min analysis). Generally speaking, delays will differ at the two entry lanes; so the level of service of the right-turn lane needs to be differentiated from the corresponding level of service at the through and left-turn lanes. The global average delay at entries is expressed by the following equation [8, 12, 17]:

$$D_E^{ped} = \frac{D_{E,R}^{ped} \cdot Q_{E,R} + D_{E,TLT}^{ped} \cdot Q_{E,TLT}}{Q_{E,R} + Q_{E,TLT}} \tag{17}$$

where $D_{E,R}^{ped}, Q_{E,R}, D_{E,TLT}^{ped}, Q_{E,TLT}$ are respectively delays and flow rates at the two lanes of the entry E. In order to define the level of service at each entry lane valuable indications can be given by NCHRP Report 672 [18] (see table 3).

Table 3. Level of Service

| Control Delay (s/veh) | Level of Service by Volume-to-Capacity Ratio | |
|-----------------------|--|-----------|
| | $v/c \leq 1$ | $v/c > 1$ |
| 0-10 | A | F |
| 10-15 | B | F |
| 15-25 | C | F |
| 25-35 | D | F |
| 35-50 | E | F |
| > 50 | F | F |

The following graphics illustrate the values of Control Delay D_E and the levels of service at entries as a function of the intensity of entry flows ($Q_{E,R}$, $Q_{E,TLT}$), pedestrian flows Q_{ped} , degrees of saturation of lanes and circulating flows on the ring $q_k = Q_{c,e} + Q_{c,i}$.

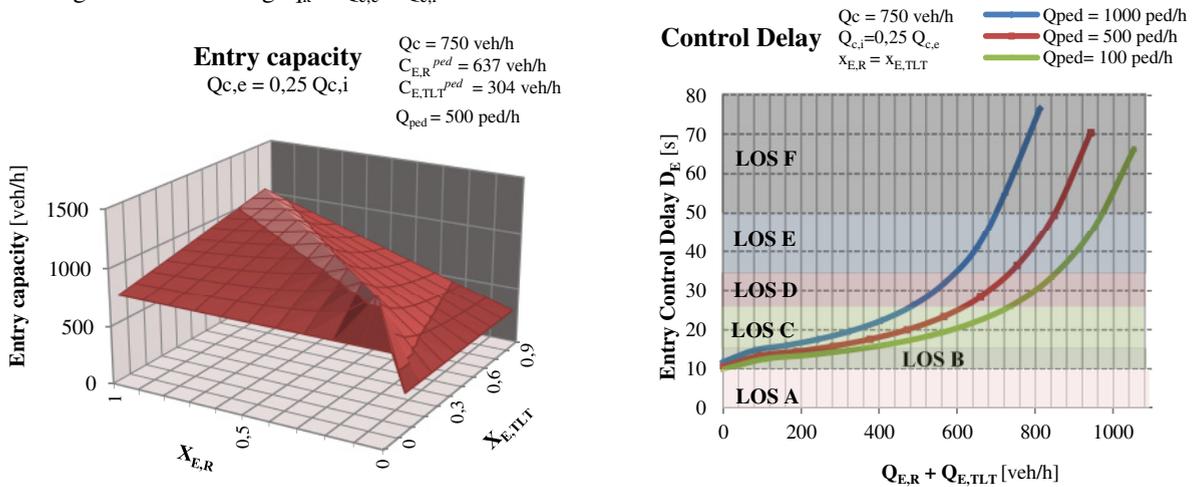


Fig. 6. Entry capacity and average delay as a function of the total entry flow and pedestrian traffic

6. Conclusions

The roundabout intersections with a turbo-shaped geometrical scheme (turbo roundabouts) are characterized by the physical separation between lanes, both at entries and on the ring. Given the positive effect on the moderate running speeds and the potential improvement of safety conditions, they are appropriate to be implemented above all in urban contexts. In these areas, the simultaneous presence of vehicles and pedestrians requires an accurate evaluation of the operational conditions of intersections, considering that pedestrian flows (often with quite a significant intensity) are generally given priority over vehicle flows. This paper describes a procedure to analyse the operational conditions of turbo roundabout intersections by assessing the combined effect of heavy and light vehicles and crossing pedestrian flows (near roundabout entries) on entry capacity. The analytical model suggested shows that each entry capacity and the relevant vehicle delays are influenced by single lane capacities, by the opposite flow, by the combination of circulating flows on ring lanes, by user behaviours (when formulations based on the *Gap acceptance theory* are implemented), by the balance of the traffic demand on each leg and by the intensity of the pedestrian traffic.

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