POTENTIAL ACCIDENT RATE OF TURBO-ROUNDABOUTS

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ABSTRACT

Turbo-roundabouts are a particular road intersection layout, designed to increase the safety of double-lane roundabouts, while maintaining their excellent capacity.

The main feature of this new concept of roundabout is the impossibility to move from one lane to another, provided by physical barriers marking the lanes. This helps to prevent side collisions crossing the roundabout.

The paper shows an application to turbo-roundabouts of a potential accident rate model, aiming to evaluate their safety improvement.

The model is based on the concept of potential conflict: each vehicle involved in a general intersection performs a series of maneuvers which may or may not imply a crash, according to the actual traffic. The number of accidents related to each critical maneuver is proportional to the number of times this maneuver occurs at the intersection.

In order to define the critical maneuvers, and hence the relevant potential conflicts, specific crash typologies for roundabouts are adopted.

Traffic volumes are required, to evaluate the expected number of accidents, and also probabilities of accident, i.e. accident / potential conflicts, for every critical maneuver.

These ratios were obtained by a model calibration, based on actual accident and traffic data recorded on conventional single-lane and double-lane roundabouts.

The model was then used to compare four-leg turbo-roundabouts to conventional roundabouts, by varying different parameters, as lane number, turning patterns and traffic flows.

The comparisons have taken into account only basic differences in layout, without dealing with other relevant features, such as geometric elements or marking options, that could also play a role in determining safety performances of a roundabout.

Considering all the limits of the analysis, however, the results obtained show that turbo-roundabouts can significantly decrease the accident rate with respect to conventional roundabouts, by eliminating conflicts between circulating and exiting vehicles.

INTRODUCTION

The model adopted for the analyses described in this paper is the same presented in (Mauro and Cattani, 2004) for single-lane roundabouts, and later extended to the double-lane case.

The model is based on the concept of “potential conflict” (Ha and Berg, 1995): each vehicle involved in a general intersection performs a series of maneuvers that may or may not imply a crash, depending on real traffic conditions. The number of crashes related to each critical maneuver is proportional, through a coefficient c_i, to the number of times that this maneuver is performed at the intersection.

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Therefore, to apply these concepts to roundabouts, it was necessary to identify risky maneuvers that occur crossing this kind of intersection: a literature review has been performed, to identify the causes of the crashes recorded at roundabouts.

At single-lane roundabouts, as demonstrated for example in (Guichet, 1993) the most frequent accident typologies are: collision due to failure to yield, run-off the road (towards the circulatory roadway center or side, or towards the splitter islands), rear-end crash at entry.

As regards double-lane roundabouts, another crash typology has to be considered, that is to say the circulating-exiting collision, which mainly involves two-wheeled vehicles (Mauro and Cattani, 2005).

The four crash typologies are shown in Figure 1. They include almost 80% of the crashes that occur at roundabouts. The remaining crashes belong to other numerous categories, whose single incidence is very low.

Thus, these four crash typologies have been considered as reference to identify the maneuvers or, more generally, the circumstances related to each crash.

After being identified, the model was calibrated, analyzing actual traffic and accident data collected in Trento, Italy, regarding conventional single-lane and double-lane roundabouts.

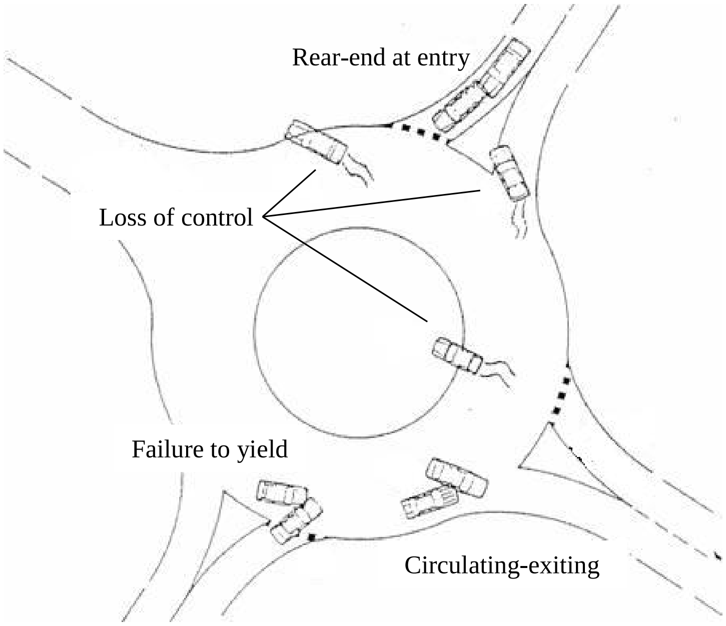

FIGURE 1 Main typologies of crashes occurring at roundabouts.

Turbo-roundabouts or spiral-roundabouts were proposed for the first time in (Fortuijn and Harte, 1997), to minimize the side collision risk in double-lane roundabouts. The goal is achieved by physical separation of the entry and the circulatory lanes, that forces the driver to choose his entry lane (left or right) on the basis of his turning destination. An example of turbo-roundabout layout is shown in Figure 2.

Afterwards, turbo-roundabouts were introduced in the Netherlands and in other European countries, and proved to have good safety and also operational performances (a comparative analysis of traffic performances of turbo-roundabouts and conventional roundabouts is presented for example in (Mauro and Branco, 2009)).

In this work, the model calibrated for single- and double-lane roundabouts is adopted to compare the safety performances of the turbo-roundabouts with the conventional double-lane layouts and to evaluate the effect of the lack of lateral collisions on the overall accident rate of the intersection.

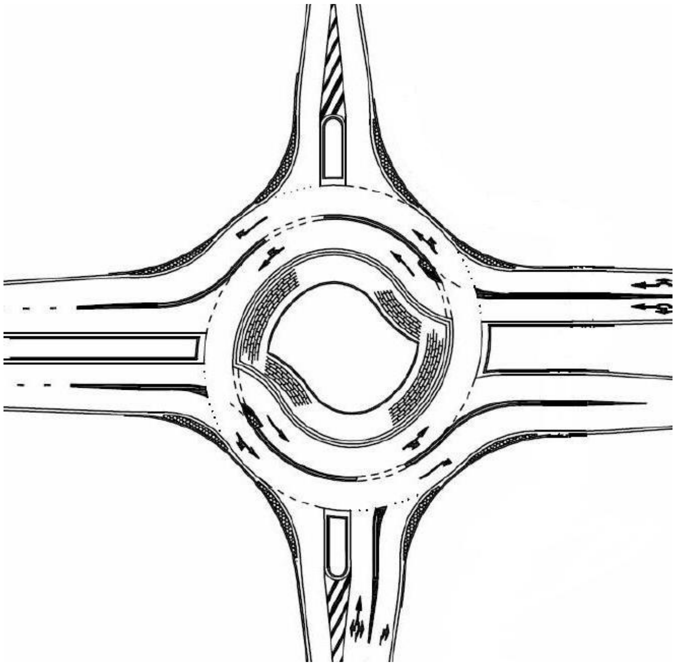

FIGURE 2 Turbo-roundabout.

MODEL DESCRIPTION

Since the key concept of the model is the evaluation of the potential conflicts number, it is useful to present an overview of the criteria used to quantify it, for each of the four crash typologies considered.

Collision for failure to yield

A first circumstance leading to this kind of crash can be due to the user's wrong evaluation of the gap available between the vehicles traveling on the circulatory roadway. Thus, the user leaves the entry without the necessary safety gap and collides with the arriving vehicle. These maneuvers assume that the entering vehicle starts from a standing start.

The entry into the circulatory roadway can be modeled by the gap acceptance theory: all the intervals inferior to the critical gap are discarded by the drivers, whereas the superior ones are accepted. To determine the number of potential conflicts it is here assumed that the intervals markedly inferior to the critical one are always discarded, whereas the ones of higher length are not considered risky: the potential dangerous situations occur when there are intervals with a width near to the critical length. Therefore this band of "dangerous" intervals has been set between $t_{inf} = 3$ s and $t_{sup} = 5$ s, with a mean value lower than the average critical gap, which ranges from 4,1 to 4,6 s according to the Highway Capacity Manual (HCM, 2001).

The portion of "dangerous" intervals with respect to their total amount is easily calculable, assuming a statistical distribution of the gaps between the circulating vehicles.

It has been supposed that such gaps are distributed in an exponential way for volumes up to 400 veh/h and according to Erlang's distribution for major flows, with a parameter K = 2 for flows minor to 1000 veh/h and with K = 3 for superior volumes (Drew, 1968).

The hourly number of potential conflicts can be defined as:

$$N_{1a} = Q_e \cdot (1 - P(0)) \cdot P(t_{inf} < t < t_{sup}) \tag{1}$$

where Q_e is the entering flow, 1 – P(0) represents the probability of having at least one vehicle waiting at the entry and consequently of having the probability of stopping before the entry for an arriving vehicle, and P ($t_{inf} < t < t_{sup}$) shows the probability that the gap between two vehicles traveling on the circulatory roadway is included in the band previously described.

P(0) calculation - that is the probability of having no vehicles waiting at entry - is carried out in two different ways: one for single-lane and another for double-lane roundabouts.

For single-lane entries, according to the queuing theory, the probability of having at least one waiting vehicle is ρ (that is the ratio of the entering volume Q_e to the capacity C of the entry). Therefore P(0) equals (1 – ρ).

At double-lane entries, the calculation of P(0) must be performed separately for each lane, knowing the share of vehicles on the two lanes, P_{left} and P_{right} (with $P_{left} + P_{right} = 1$). It can be shown that $P(0)_{left} = \frac{1-\rho}{1-\rho \cdot P_{right}}$ and $P(0)_{right} = \frac{1-\rho}{1-\rho \cdot P_{left}}$, with ρ referred to the whole entry demand and capacity.

The probability P ($t_{inf} < t < t_{sup}$) is explicated in the following way according to the circulating flow Q_c and consequently to the relative distribution of vehicular gaps:

Q_c < 400 veh/h

$$P(t_{inf} < t < t_{sup}) = e^{-Q_c \cdot t_{inf}} - e^{-Q_c \cdot t_{sup}} \tag{2}$$

400 < Q_c < 1000 veh/h

$$P(t_{inf} < t < t_{sup}) = e^{-2Q_c \cdot t_{inf}}(1 + 2Q_c \cdot t_{inf}) - e^{-2Q_c \cdot t_{i\,sup}}(1 + 2Q_c \cdot t_{sup}) \tag{3}$$

Q_c > 1000 veh/h

$$P(t_{inf} < t < t_{sup}) = e^{-3Q_c \cdot t_{inf}}\left(1 + 3Q_c \cdot t_{inf} + \frac{9}{2}Q_c^2 t_{inf}^2\right) - e^{-3Q_c \cdot t_{sup}}\left(1 + 3Q_c \cdot t_{sup} + \frac{9}{2}Q_c^2 t_{sup}^2\right) \tag{4}$$

Whereas for single-lane roundabouts the impeding flow Q_c is represented simply by the circulating flow, at double-lane roundabouts the impeding flow for each entry lane is different: for the right lane, leading to the outer lane of the circulatory roadway, the traffic circulating on the inner lane can be excluded from the impeding flow; on the contrary, vehicles entering from the left lane have to yield to both circulating lanes: the impeding flow is hence for them the entire circulating traffic.

The second circumstance of failure to yield is connected to the non-perception of the roundabout. Unlike the situation previously described, in this case there are no vehicles waiting at the entry.

An arriving vehicle can enter the roundabout without checking in advance whether there are the right conditions, and consequently without stopping, for different possible reasons (non-perception of the roundabout due to poor visibility, driver's inattention, excessive speed, etc.). In this case, the crash probability is considered the same as the case in which the roundabout is entered “blindly”. This probability is assumed to be proportional to the circulating flow and to a time value t_{coll} representing the interval related to the transit of each vehicle within the circulatory roadway that implies a sure collision if the entry occurs during this lapse of time.

Considering average sizes of the vehicles and effective speeds both on the circulatory roadway and at entry, such interval t_{coll} equals to 2 seconds.

The hourly number of potential conflicts for this kind of crash is hence:

$$N_{1b} = Q_e \cdot P(0) \cdot t_{coll} \cdot Q_c \tag{5}$$

The term P(0) shows the probability of having no vehicles waiting at entry.

There are no differences here between single-lane and double-lane roundabouts, in terms of oncoming flow. It equals here to the entire circulating flow: in fact it can be assumed that a vehicle entering the roundabout without checking safety conditions will affect both lanes of the circulatory roadway, since it can crash into vehicles traveling on both of them.

Crashes for loss of vehicle control

As shown in the above-mentioned statistics, the collision for loss of vehicle control can occur at the entry, within the circulatory roadway or at the exit of a roundabout. Apart from the location, overspeeding is the necessary condition for the loss of control. Consequently, all the entries to the roundabout where a queue takes place are excluded from potential conflicts. The cases that require the driver to wait for a favorable interval between circulating vehicles are also excluded.

The hourly number of potential conflicts is therefore:

$$N_2 = Q_e \cdot P(0) \cdot e^{-Q_c \cdot t_c} \tag{6}$$

It derives from the probability P(0) of having no vehicles waiting at entry, and from the probability of an entering vehicle to find a gap bigger than the critical gap $e^{-Q_c \cdot t_c}$.

Also for this typology, the only difference between single-lane and double-lane roundabouts is that - regarding only the latter - left and right lane must be considered independently.

Rear-end at entry

The necessary condition to cause a crash is the presence of at least one waiting vehicle at the entry of the roundabout. The rear-end can occur directly if the queuing vehicle does not succeed in stopping in time or, more frequently (Guichet, 1993), during the discontinuous lining up that leads to the circulatory roadway.

In this case, the hourly number of potential conflicts is:

$$N_3 = Q_e \cdot \left(1 - P(0)\right) \tag{7}$$

Also for rear-end, the number of lanes only implies that it could be necessary to calculate two values of P(0), one for each lane.

Circulating-exiting collision

When two four-wheeled vehicles are involved, this typology is mainly linked to the potential conflict between vehicles exiting the roundabout from the inner lane of the circulatory roadway and vehicles traveling on the outer lane (toward the next exit).

The drivers intending to leave the inner lane have to wait for a suitable gap between two non-exiting vehicles of the outer flow. Risky turns occur when the outer vehicle heads for the next exit. As for the potential conflict due to the failure to yield without stopping, a time gap relating to each vehicle on the outer lane can be defined. If the vehicle leaving the inner lane crosses the outer one during this time interval, it will crash into the other. As already done for the entry without stopping, this time t_{coll} is assumed equal to 2 s, considering that the crossing maneuver is almost equal to the accidental entry in the circulatory roadway (Figure 3).

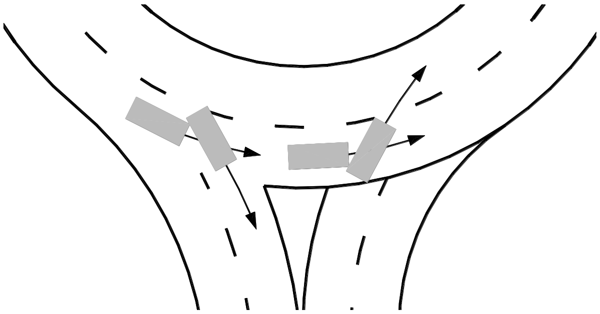

FIGURE 3 Potential conflict related to the crossing maneuvers entering and exiting the roundabout.

The number of potential conflicts N_4 is hence similar to N_{1b}, but it is not necessary to consider possible queues.

$$N_4 = Q_{out,int} \cdot t_{coll} \cdot Q_{c,ext} \tag{8}$$

From the formulations presented, it is clear that the total number of potential hourly conflicts at a roundabout depends on the entering volumes in the different legs, but it is not directly proportional to these volumes. In fact, there is the influence of other factors, such as circulating flow (which depends on the traffic demand at the other entries and on the turning percentages) and capacity of the entries (which also depends on circulating traffic).

Briefly, the number of potential conflicts depends on the operative conditions recorded at an intersection, even with the same flows.

Adopting the model this paper deals with, it is necessary to know - or to define - a trend in time of the traffic volume in order to evaluate the potential accident rate of an intersection, whether it be traditional or roundabout.

For instance, the calculation of the potential accident rate per year cannot be reliable if only the values of the total annual traffic concerning the intersection are taken into account; it is in fact necessary to know or assume its distribution in the period considered.

Once the number of potential conflicts for each kind of maneuver has been obtained, the potential accident rate is calculated by multiplying each value for its relative coefficient c_i, and then by adding up all the products.

Concerning the model here presented, after having considered as significant the crash typologies previously described, the hourly potential accident rate (PAR) at a roundabout is the result of the sum:

$$PAR = \sum_i c_i N_i = c_{1a}\ N_{1a} + c_{1b}\ N_{1b} + c_2\ N_2 + c_3\ N_3 + c_4\ N_4 \tag{9}$$

MODEL CALIBRATION

In the previous chapter, the number of potential conflicts N_i at a roundabout was defined as a function of the traffic data of the roundabout. To evaluate PAR it is necessary to know the coefficients c_i that show how often - on average - a crash is registered in comparison with the number of potential conflicts.

These coefficients were evaluated with a calibration of the model, performed analyzing actual traffic data and actual accident data, collected on six intersections in Trento, Italy: three single-lane roundabouts and three double-lane roundabouts.

Accident data were available for a period up to eight years, depending on when the roundabout was built.

Traffic data came from automatic devices that provide 24 hour measurements. The traffic trend could be defined hour by hour for an entire week (chosen to represent annual average conditions), enabling an accurate evaluation of the number of potential conflicts.

Knowing the traffic patterns, the capacity procedure defined in (Wu, 1997) was adopted in order to calculate the capacity of each entry. This procedure was chosen for the German national guidelines HBS 2001, and permits to deal both with single-lane and double-lane roundabouts. Its formulation is:

$$C = 3600 \cdot \left(1 - \frac{t_m \cdot Q_c}{n_c}\right)^{n_C} \cdot \frac{n_e}{t_f} \cdot e^{-Q_c\left(t_c - \frac{t_f}{2} - t_m\right)} \tag{10}$$

where:

Q_c = circulating flow [pc/h]

n_e = number of lanes at the entry

n_c = number of lanes of the circulatory roadway

t_c = critical gap: 4.12 s

t_f = follow-up time: 2.88 s

t_m = minimal gap between vehicles on the circulatory roadway: 2.10 s.

Table 1 reports an example of the calculations made to evaluate the potential accidents during 24 hours, for one entry of one (single-lane) roundabout.

The annual number of potential conflicts, calculated for another of the analyzed roundabouts, is shown in Table 2, together with the accident data and the coefficients obtained dividing the accidents by the potential conflicts.

The whole set of coefficients resulted from the calibration of the model is summarized in Table 3.

For a detailed explanation of the calibration procedure, see (Mauro and Cattani, 2004) along with (Mauro and Cattani, 2005).

TABLE 1 Traffic Data And Potential Conflicts Evaluated For One Of The Analyzed Roundabouts, For A Period Of 24 Hours

Roundabout: *Piedicastello* (single-lane) - Entry nr. 1: *via Brescia*

Traffic data				Probability values (Mauro and Cattani, 2005)			Potential conflicts, calculated as in (Mauro and Cattani, 2005)			
hour	Q_e (entering flow)	Q_c (circulating flow)	C (capacity)	ρ (=Q_e / C)	P ($t_{inf} < t < t_{sup}$)	P ($t > t_c$)	Failure to yield after stopping	Failure to yield without stopping	Run-off the roadway	Rear-end collision
0:00-1:00	27	32	1220	0.02	0.017	0.962	0	0	25	1
1:00-2:00	18	21	1231	0.01	0.011	0.975	0	0	17	0
2:00-3:00	6	11	1240	0.00	0.006	0.987	0	0	6	0
3:00-4:00	2	7	1243	0.00	0.004	0.991	0	0	2	0
4:00-5:00	8	19	1232	0.01	0.010	0.977	0	0	8	0
5:00-6:00	31	38	1215	0.03	0.020	0.955	0	1	29	1
6:00-7:00	166	97	1161	0.14	0.048	0.889	1	8	126	24
7:00-8:00	661	370	923	0.72	0.137	0.639	65	39	120	474
8:00-9:00	685	418	883	0.77	0.169	0.732	90	36	113	530
9:00-10:00	398	313	972	0.41	0.123	0.685	20	41	161	163
10:00-11:00	300	333	954	0.31	0.128	0.669	12	38	137	94
11:00-12:00	256	290	991	0.26	0.117	0.705	8	31	134	66
12:00-13:00	260	343	946	0.27	0.130	0.661	9	36	125	71
13:00-14:00	348	333	954	0.36	0.128	0.669	16	41	148	127
14:00-15:00	407	351	940	0.43	0.132	0.655	23	45	151	177
15:00-16:00	387	353	938	0.41	0.133	0.653	21	45	148	160
16:00-17:00	402	373	921	0.44	0.137	0.637	24	47	144	175
17:00-18:00	396	504	814	0.49	0.202	0.657	39	57	134	193
18:00-19:00	334	448	859	0.39	0.181	0.705	24	51	144	130
19:00-20:00	229	286	994	0.23	0.116	0.708	6	28	125	53
20:00-21:00	164	150	1113	0.15	0.071	0.834	2	12	116	24
21:00-22:00	117	96	1162	0.10	0.048	0.890	1	6	93	12
22:00-23:00	78	77	1180	0.07	0.039	0.912	0	3	67	5
23:00-24:00	71	76	1180	0.06	0.039	0.913	0	3	61	4
Daily total	5751	5339	-	-	-	-	361	568	2334	2484

TABLE 2 Weekly And Annual Potential Conflicts And Calculation Of The Model Coefficients, For One Of The Roundabouts Considered

Roundabout: *Bren Center* (double-lane)	Failure to yield after stopping	Failure to yield without stopping	Run-off the roadway	Rear-end collision	Circulating-exiting collision
Entry nr. 1 - via Bolzano	3697	6711	54826	62416	3717
Entry nr. 2 - via Brennero	3940	10226	52856	31337	783
Entry nr. 3 - via Zambra	3077	4436	7928	19592	2128
Entry nr. 4 - via Trener	2192	11611	12785	11706	2545
Potential conflicts / week	**12,906**	**32,984**	**128,395**	**125,051**	**9,174**
Weekly flow			**284,929**		
Flow / potential conflicts	**22.1**	**8.6**	**2.2**	**2.3**	**31.1**
Potential conflicts / year	**672,965**	**1,719,857**	**6,694,888**	**6,520,512**	**478,335**
	c_1		c_2	c_3	c_4
Total crashes / year	7.23		0.89	1.92	23.02
Coefficients (total crashes)	**3.02×10^{-6}**		**1.32×10^{-7}**	**2.94×10^{-7}**	**4.81×10^{-5}**
Injury crashes / year	3.25		0.30	0.89	3.99
Coefficients (injury crashes)	**1.36×10^{-6}**		**4.41×10^{-8}**	**1.36×10^{-7}**	**8.33×10^{-6}**

TABLE 3 Results Of The Model Calibration

Accident type and correspondent model coefficient	**Total crashes**			**Injury crashes**		
	min value*	**max value***	**mean value**	**min value***	**max value***	**mean value**
Failure to yield - c_1	4.1×10^{-7}	3.0×10^{-6}	**1.7×10^{-6}**	2.1×10^{-7}	1.4×10^{-6}	**6.5×10^{-7}**
Run off the roadway - c_2	1.7×10^{-8}	2.2×10^{-7}	**1.1×10^{-7}**	1.7×10^{-8}	4.4×10^{-8}	**1.5×10^{-8}**
Rear-end - c_3	9.8×10^{-8}	2.9×10^{-7}	**2.3×10^{-7}**	3.3×10^{-8}	1.4×10^{-7}	**8.9×10^{-8}**
Circulating-exiting - c_4	2.2×10^{-6}	4.8×10^{-5}	**1.9×10^{-5}**	2.2×10^{-7}	8.3×10^{-6}	**3.3×10^{-6}**

* min and max values express the range of results obtained from different roundabouts

APPLICATION OF THE MODEL TO TURBO-ROUNDABOUTS

The main difference between turbo-roundabouts and conventional layouts consists of the lack of circulating-exiting conflicts, which are eliminated by the divided lanes of the turbo-roundabouts, both at entries and on the circulatory roadway.

In a turbo-roundabout, the driver, before entering the roundabout, has to choose a lane depending on the desired destination.

Functioning rules of turbo-roundabouts are essentially the same as those for the "normal" roundabouts: entering drivers must give way to circulating vehicles. Hence one can expect that in both types of roundabout the ratios between potential conflicts and actual accidents, that is the coefficients of the potential accident rate model, are roughly the same .

However, such statement could not be verified by the authors, because of the lack of turbo-roundabouts in Italy. Therefore, the model could not undergo a specific calibration for this new layout.

Bearing in mind these limitations, the model was applied to turbo-roundabouts only to give a preliminary evaluation of the reduction of potential conflicts and - more important - of the potential accident rate, that this layout can lead to, with respect to double-lane roundabouts.

The coefficients of the model used for the comparisons remain the ones resulting from the calibration previously described.

What changes is the number of potential conflicts, calculated considering the actual functioning rules of the turbo-roundabouts. In particular, entry flows are split on the lanes depending on their destination, as are the circulating flows.

Moreover, a capacity procedure specific for turbo-roundabouts needs to be used. For the right lane of the entry, give way process is definitely analogous to conventional roundabouts: capacity is hence calculated with the Wu formulation. Since the flow merges only into one lane of the circulatory roadway, n_e and n_c are set equal to 1. Left lane of turbo-roundabouts approaches implies rather a crossing trajectory, instead leading the entering flow to merge with the circulating traffic. Therefore, to evaluate the capacity the classic Harders formula is used.

$$C_{left} = Q_c \frac{e^{-Q_c \cdot t_c / 3600}}{1 - e^{-Q_c \cdot t_f / 3600}} \tag{11}$$

where:
Q_c = circulating flow [pc/h]
t_c = critical gap [s]
t_f = follow-up time [s]

Values for critical gap and follow-up time are that provided by HCM 2000 (Transportation Research Board, 2001) for through traffic at unsignalized intersections: t_c = 6,5 s; t_f = 4,0 s. This values are probably rather conservative, dealing with roundabouts, but it was already shown (Mauro and Cattani, 2004) that the model has a low sensitivity to the particular capacity formulation adopted.

Capacity for right and left lane are combined depending on the actual approach layout: if it comes at the end of a multilane highway (with two lane per direction), capacity values are simply their sum. On the contrary, if the double-lane approach is a flare of a two-lane highway (with one lane per direction), total entry capacity is the sum of the critical lane capacity and the correspondent flow on the non-saturated lane. Its value can be obtained from:

$$C_{tot} = \frac{Q_{e,right} + Q_{e,left}}{\max\left(\frac{Q_{e,right}}{C_{right}}, \frac{Q_{e,left}}{C_{left}}\right)} \tag{12}$$

where:
Q_e = entering flow [pc/h]

Finally, calculation of potential conflicts at turbo-roundabouts has to consider a specific issue: where at one entry two different lane capacity values are calculated, potential conflicts evaluation proceeds independently for each lane. Their sum forms the overall potential conflicts number for that approach.

COMPARISON BETWEEN CONVENTIONAL AND TURBO-ROUNDABOUTS

Using the model, a comparison between safety performances of conventional and turbo-roundabouts was performed.

For both categories of roundabouts two reference layouts were defined. They consider only the effect on safety of the number of lanes. Other geometric parameters that can influence conflict probability (e.g. circulatory roadway radius, exit radius, distance and angle between adjacent legs, etc.) are not reflected by the analysis.

The two layouts for four-leg turbo-roundabouts are (Figure 4):

- four double-lane approaches; one axis (legs 2 and 4) has prevailing flows over the other
- two double-lane approaches, for the main traffic direction, and two single-lane legs, for the minor approaches

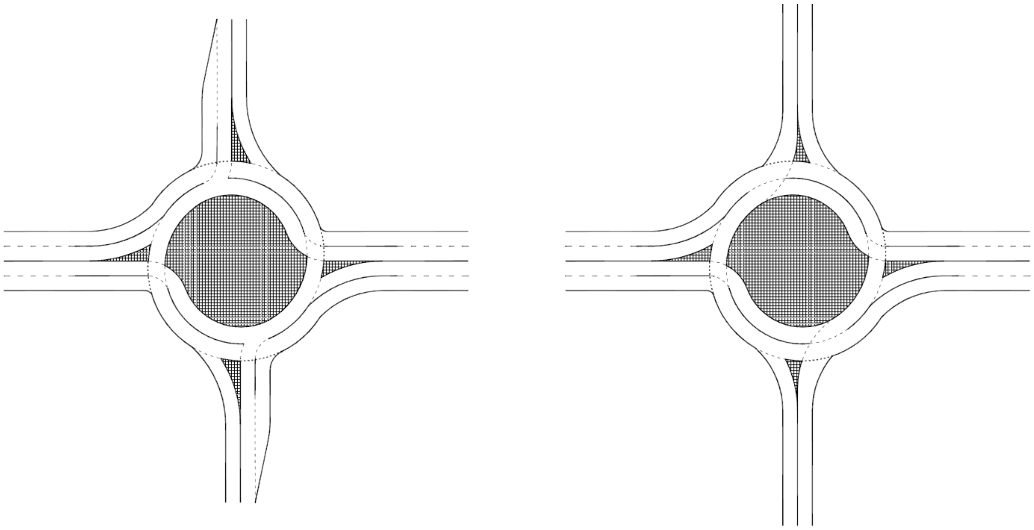

FIGURE 4 Turbo-roundabout layouts for comparison

The traditional reference double-lane layouts, whose safety performances are compared with the turbo-roundabout, are also two (Figure 5):

- four double-lane approaches and double-lane circulatory roadway
- two double-lane approaches, for the main traffic direction, and two single-lane legs, for the minor approaches, double-lane circulatory roadway

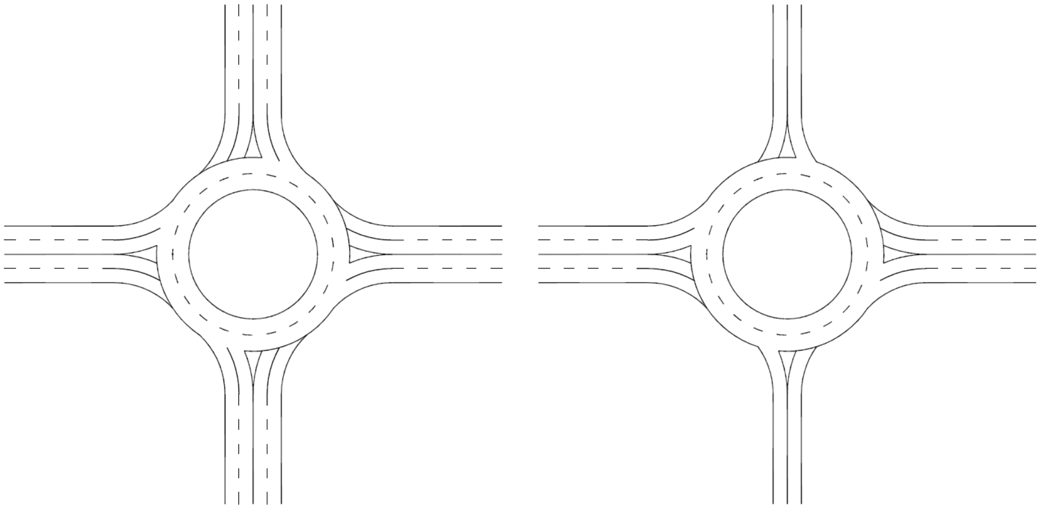

FIGURE 5 Double-lane roundabout layouts for comparison.

The test was performed defining specific standard traffic conditions, consisting in average daily volumes expressed by the vector

$$AADT = [10000, 2000, 10000, 2000]$$

and a distribution of the flows along the standard day as shown in Figure 6.

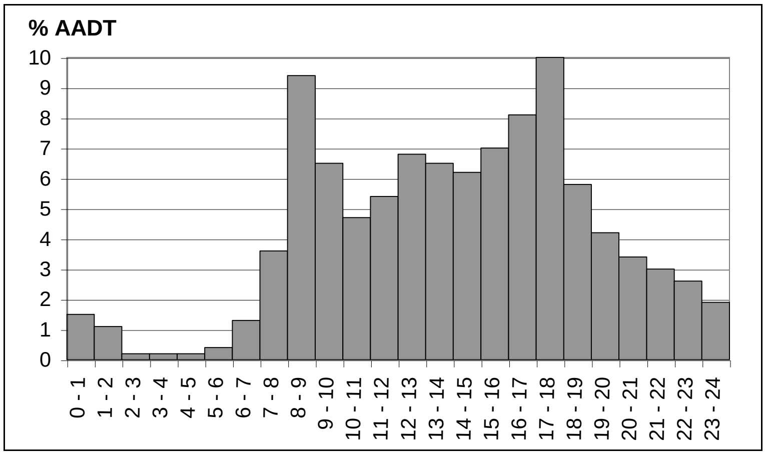

FIGURE 6 Daily traffic trend used for the test.

It is worth to remember that this detailed traffic flow definition is required to use the model, since the overall number of potential conflict has to be calculated and the potential conflict occurrence is dependent on the traffic conditions.

The comparisons considered different turning patterns, to reflect different behaviors of conventional and turbo-roundabouts with respect to various traffic conditions. The matrixes of turning shares are listed below: they include extreme reference situations, expressed by only right (P1) or only left (P5) turns and by uniform sharing between the three possible destinations for all approaches (P3), and then more realistic cases, with two different patterns having most turns leading to a main road (P2 and P4).

Each element $p_{i,j}$ in the matrix represents the share of vehicles exiting towards leg j, with respect to all vehicles entering from leg i.

$$P1 = \begin{vmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 \end{vmatrix} \quad P2 = \begin{vmatrix} 0 & 0.65 & 0.05 & 0.30 \\ 0.05 & 0 & 0.05 & 0.90 \\ 0.05 & 0.30 & 0 & 0.65 \\ 0.05 & 0.90 & 0.05 & 0 \end{vmatrix} \quad P3 = \begin{vmatrix} 0 & 0.33 & 0.33 & 0.33 \\ 0.33 & 0 & 0.33 & 0.33 \\ 0.33 & 0.33 & 0 & 0.33 \\ 0.33 & 0.33 & 0.33 & 0 \end{vmatrix}$$

$$P4 = \begin{vmatrix} 0 & 0.30 & 0.05 & 0.65 \\ 0.05 & 0 & 0.05 & 0.90 \\ 0.05 & 0.65 & 0 & 0.30 \\ 0.05 & 0.90 & 0.05 & 0 \end{vmatrix} \quad P5 = \begin{vmatrix} 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{vmatrix}$$

Dealing with double-lane roundabouts, the calculation of the number of potential conflicts must then include a parameter in order to take into account the lane chosen while entering the intersection. The distribution on the left and right lane for each turn (left, straight on and right) can be summarized in a matrix containing the percentage of vehicles entering the left (or the right) lane for every origin and destination. This matrix reflects drivers' behavior.

For conventional layouts, every driver can choose the lane to enter the roundabout. For turbo-roundabouts, however, this freedom is granted only for few turns.

The matrixes adopted for the comparisons are the following. The values show the share of vehicles entering on the left lane (P_{left}), for each turn. For example, $P_{left\ 3,1}$ = 30% means that vehicles traveling from leg 3 to leg 1 enter the roundabout 30% on the left lane and 70% on the right lane.

Double-lane roundabouts

	1	2	3	4
1	0	0	30%	70%
2	70%	0	0	30%
3	30%	70%	0	0
4	0	30%	70%	0

Turbo-roundabouts

	1	2	3	4
1	0	30%	100%	100%
2	100%	0	0	40%
3	100%	100%	0	30%
4	0	40%	100%	0

The lane utilization percentage (P_{left} and P_{right}, with $P_{left} + P_{right} = 1$) leads to the calculation of the values Q_e and Q_c referred to the two lanes ($Q_{e,left}$, $Q_{e,right}$ and $Q_{c,left}$, $Q_{c,right}$ respectively, see Figure 7). To determine the circulating flow, vehicles entering the left lane are assumed to travel on the left (inner) lane, whereas vehicles entering the right lane will stay on the right (outer) lane.

In turbo-roundabouts, however, the lane followed by drivers on the circulatory roadway - exactly as the lane at the entry - is mostly determined by the destination leg.

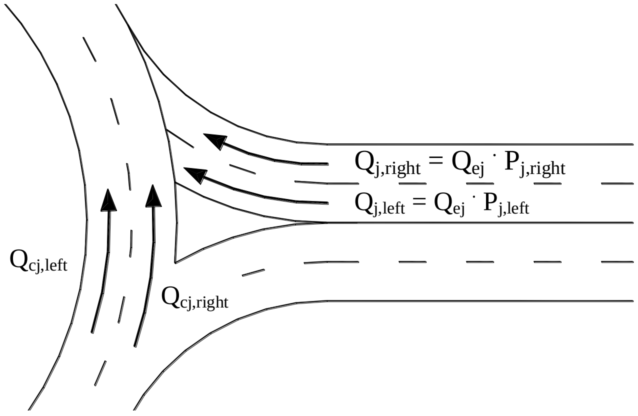

FIGURE 7 Entering and circulating flow distribution on the two lanes.

RESULTS

The next tables summarize the results of the comparison, for the two couples of layouts considered: Table 4 and Table 5 show potential conflicts and potential accident rate for the conventional double-lane roundabout, with four double-lane approaches, and the turbo-roundabout also with four double-lane approaches; Table 6 and Table 7 contain the same outcomes for conventional double-lane roundabout and turbo-roundabout, both with two double-lane main approaches and two single-lane minor approaches.

It is clear that, beside not negligible differences in terms of potential conflicts, in both examples the final results, i.e. the potential accident rates, are strongly reduced at turbo-roundabouts. The size of this safety gain is dependent on the traffic pattern, and decreases considering injury crashes instead of total accidents, but the difference is surely significant. For example, with matrixes P2 and P4, the most representative of real traffic conditions, turbo-roundabouts reduce total crashes of about 40-50%, and injury crashes of 25-30%.

The effect is due to the lack of circulating-exiting conflicts, that cause a relevant share of crashes at conventional double-lane roundabouts.

Variations in the recurrence of other conflicts types do not imply sizable differences in the expected annual accident numbers. Such variations mainly depend on capacity performance of the roundabout: lesser the capacity, more frequent the queues and hence higher the number of rear-end and failure-to-yield-after-stopping conflicts. Besides, it can be seen that the sum of the conflicts due to failure to yield, and also the number of potential accidents, remains approximately constant for conventional and turbo-roundabouts: an increase in failure-to-yield-after-stopping conflicts is compensated for by a decrease in failure-to-yield-without-stopping conflicts, or vice versa.

TABLE 4 Potential Conflicts For Conventional And Turbo Roundabouts, Case 1: Double-Lane Roundabout Vs. Turbo-Roundabout 1

Accident type	Annual potential conflicts (matrix P4)		
	2-lane roundabout	Turbo-roundabout	Difference (%)
Failure to yield after stopping	60,299	176,167	192%
Failure to yield w/o stopping	812,104	656,149	-19%
Run off the roadway	6,783,144	5,675,306	-16%
Rear-end	1,424,534	2,405,151	69%
Circulating-exiting	91,719	-	-100%

TABLE 5 Potential Accident Rate For Conventional And Turbo Roundabouts, Case 1: Double-Lane Roundabout Vs. Turbo-Roundabout 1

Accident type	Annual potential accidents					
	2-lane roundabout		Turbo-roundabout		Difference (%)	
	Total crashes	Injury crashes	Total crashes	Injury crashes	Total crashes	Injury crashes
Failure to yield after stopping	0.10	0.04	0.30	0.11	+200%	+175%
Failure to yield w/o stopping	1.38	0.53	1.12	0.43	-19%	-19%
Run off the roadway	0.75	0.10	0.62	0.09	-17%	-10%
Rear-end	0.33	0.13	0.55	0.21	+67%	+62%
Circulating-exiting	1.74	0.30	-	-	-100%	-100%
Total (matrix P4)	4.30	1.10	2.59	0.84	**-40%**	**-24%**
Total (matrix P1)	1.31		0.96		**-27%**	
Total (matrix P2)	3.66		1.92		**-48%**	
Total (matrix P3)	7.19		3.50		**-51%**	
Total (matrix P5)	16.34		1.40		**-91%**	

TABLE 6: Potential Conflicts For Conventional And Turbo Roundabouts, Case 2: Double-Lane Roundabout (With Two Single-Lane Approaches) Vs. Turbo-Roundabout 2

Accident type	Annual potential conflicts (matrix P4)		
	2-lane roundabout	Turbo-roundabout	Difference (%)
Failure to yield after stopping	160,393	188,803	+18%
Failure to yield w/o stopping	746,927	751,600	+1%
Run off the roadway	6,434,673	5,873,548	-9%
Rear-end	1,633,526	2,215,532	+36%
Circulating-exiting	140,781	-	-100%

TABLE 7: Potential Accident Rate For Conventional And Turbo Roundabouts, Case 2: Double-Lane Roundabout (With Two Single-Lane Approaches) Vs. Turbo-Roundabout 2

Accident type	Annual potential accidents					
	2-lane roundabout		Turbo-roundabout		Difference (%)	
	Total crashes	Injury crashes	Total crashes	Injury crashes	Total crashes	Injury crashes
Failure to yield after stopping	0.27	0.10	0.32	0.12	+19%	+20%
Failure to yield w/o stopping	1.27	0.49	1.28	0.49	+1%	0%
Run off the roadway	0.71	0.10	0.65	0.09	-8%	-10%
Rear-end	0.38	0.15	0.51	0.20	+34%	+33%
Circulating-exiting	2.67	0.46	-	-	-100%	-100%
Total (matrix P4)	5.30	1.30	2.76	0.90	**-48%**	**-31%**
Total (matrix P1)	1.20		0.74		**-38%**	
Total (matrix P2)	5.05		2.43		**-52%**	
Total (matrix P3)	9.07		3.31		**-64%**	
Total (matrix P5)	24.20		2.06		**-91%**	

Sensitivity with respect to the traffic volumes

To check possible variations in results of the comparison between conventional and turbo-roundabouts, the model was applied to both layouts with different values of the daily traffic flows. Both main and secondary flow have been made greater: the former from 10.000 veh/day up to 15,000, the latter from 2,000 to 7,000.

The potential accidents generally show a linear growth with increasing traffic volumes. This trend appears to be faster for conventional double-lane roundabouts: as a consequence, the reduction of the potential accident rate that turbo-roundabouts assure, with respect to conventional lay-outs, becomes higher when traffic flows are bigger.

For instance, with traffic patterns expressed by matrixes as P2 or P4, the difference in the potential accident rate is about 50% with the basic daily traffic volumes considered (10,000 and 2,000, for main and secondary flows respectively), and is equivalent to 65-70% if one of the flows grows by 5,000 veh/day (10,000 to 15,000 or 2,000 to 7,000).

CONCLUSIONS

This paper refers to an application of a potential accident rate model to turbo-roundabouts.

The model was defined and calibrated only for conventional roundabouts. Moreover, calibration has considered few intersections, and cannot be considered representative of a whole range of roundabouts.

For these reasons, the application of the model to the analysis of turbo-roundabouts implies a somehow arbitrary extension of the coefficients' significance. Hence, the use of the model to deduce the turbo-roundabouts potential accident rate can only give a preliminary indication of the advantages in terms of safety that this new layout can bring. Furthermore, the comparison between conventional and turbo-roundabouts has considered "ideal" layouts, not investigating the effects of many possible variations in the geometric features, for each single type of roundabout.

Even considering these limitations, the results appear to have great significance: in the different layouts and traffic conditions analyzed, turbo-roundabouts provide reductions of the number of total potential accidents between 40% and 50%, and reductions of the number of potential accidents with injuries between 20% and 30%.

The reliability of these conclusions is strictly related to the capability of the model, calibrated from the analysis of conventional roundabouts, to correctly evaluate risky conditions at turbo-roundabouts.

More reliable indications about the safety performances of turbo-roundabouts can be obtained only with the analysis of existing intersections, that can lead to the calibration of a potential accident rate model, specific for this kind of roundabout arrangement.

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