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Environmental, functional and economic criteria for comparing "target roundabouts" with one- or two-level roundabout intersections

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ABSTRACT

The article describes a criterion based on functional, environmental and economic aspects for comparing conventional roundabouts with innovative one- or two-level roundabouts. We compared the performances of eight roundabout types, differing in geometric layout, number of lanes and traffic flow regulation from each other, with regard to vehicle delays and CO_2, NO_x, $PM_{2.5}$ and PM_{10} pollutant emissions. Recently-designed roundabouts – *target roundabouts* and *flyover roundabouts* – have also been studied for their undoubted practical interest. By means of closed-form capacity models and CORINAIR methodology, several traffic simulations were carried out to examine a typical annual traffic demand curve in a suburban context, three different distribution test matrices for traffic flows (ρ1, ρ2, ρ3) and maximum annual traffic flow values Q_{max} ranging between 1300 and 3300 veh/h.

Estimating vehicle delays and annual pollutant emissions, along with construction and management costs, allowed obtaining overall costs for each roundabout examined, in function of traffic demand and several other parameters. Thanks to these analyses, we identified the roundabout types which best suit to each traffic condition.

Introduction

In the last decade new roundabout types of great practical interest have been designed, e.g. turbo-roundabouts (Fortuijn, 2009; CROW, 2008), flower-roundabouts (Tollazzi et al., 2011a; Mauro and Guerrieri, 2013a) and "C-roundabouts" (Guerrieri and Corriere, 2014).

Such intersections offer potential safety benefits (Mauro and Cattani, 2004; Pecchini et al., 2014) and, under certain traffic conditions, they provide higher capacity than conventional roundabouts (Mauro and Branco, 2010).

In the latest years numerous researches have been undertaken to compare conventional with innovative roundabout capacities (Mauro and Branco, 2010; Tollazzi, 2014). On this matter, we can distinguish two different methodological approaches: micro simulation and closed-form estimation models (Brilon et al., 1997; Brilon, 2005; Mauro, 2010; Yap et al., 2013).

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Environmental benefits of conventional roundabouts and small roundabouts compared to other intersection types - be they signalized or unsignalized – have been pointed out in a great number of researches (Coelho et al., 2006; Varhelyi, 2002; Yedla et al., 2005; Wilkinson et al., 2013; Midenet et al., 2012). On the contrary, very few studies have still investigated "environmental performances" of innovative roundabouts, which is of particular interest especially in urban and suburban contexts (Corriere et al., 2013; Guerrieri et al., 2014).

Recently, new roundabouts have been designed with a two-level carriageway which, against higher construction costs, ensure higher capacity, and therefore lower vehicle delays (Mauro and Branco, 2012) and reduced environmental costs. The article especially deals with the "target roundabout" (Tollazzi et al., 2013), i.e. a dual one-lane roundabout on two levels with right-turn bypasses, and the "four flyover roundabout" (Tollazzi, 2014), i.e. a roundabout with dedicated left-turn bypasses (slip-lanes) on major roads, whose capacity and vehicle delay can be estimated by a newly designed model.

Both the target and four flyover roundabouts were compared with other roundabout intersections, and precisely: (a) flower roundabout with stop-controlled right-turn bypass lane; (b) flower roundabout with yield-controlled right-turn bypass lane; (c) flower roundabout with free-flow right-turn bypass lane; (d) conventional roundabout with an entry lane and a ring lane; (e) conventional roundabout with an entry lane and two ring lanes; (f) conventional roundabout with two entry lanes and two ring lanes.

We used the models described in the Highway Capacity Manual (NCHRP Report 672, 2010) to assess performances of conventional roundabouts, and the model suggested by Corriere et al., 2013 for flower roundabouts by taking the modes of traffic flow regulation in slip lanes into account (Al-Ghandour et al., 2012).

The comparison between conventional and innovative one- or two-level roundabouts was made with regard to functional and economic aspects, and pollutant environmental pressure (CO_2, NO_x, $PM_{2.5}$ and PM_{10} emissions). A great number of traffic simulations were carried out by examining a typical annual traffic demand curve in suburban contexts, three different matrices of the distribution test for traffic flows (ρ1, ρ2, ρ3) and annual peak capacity values Q_{max} ranging between 1300 and 3300 veh/h.

Whenever the traffic entering a roundabout changed, we determined capacity, saturation degrees and delays for each lane, entry and entire intersection. Moreover, after setting a vehicle class distribution, with the aid of the CORINAIR methodology (Coelho et al., 2014) we assessed annual emissions from road vehicles.

Finally, we compared total costs (Mauro and Cattani, 2012) due to delays, pollutant emissions, construction and management costs for each of the eight roundabouts in question in order to identify the traffic value range which makes every roundabout type more advantageous.

Alternative types of two-level intersections

Target roundabout

The dual one-lane roundabout on two levels with right-turn bypasses – in short the "target roundabout" – was, like the flower roundabout (Tollazzi et al., 2011a,b), invented at the Centre of Road Infrastructure at the Faculty of Civil Engineering, University of Maribor, Slovenia, and is still at the development phase.

A target roundabout (Tollazzi et al., 2013) is designed as a dual one-lane roundabout with different outer diameters, located on two levels (Fig. 1), and all right-hand turners on both roundabouts have their own separate right-turn bypass

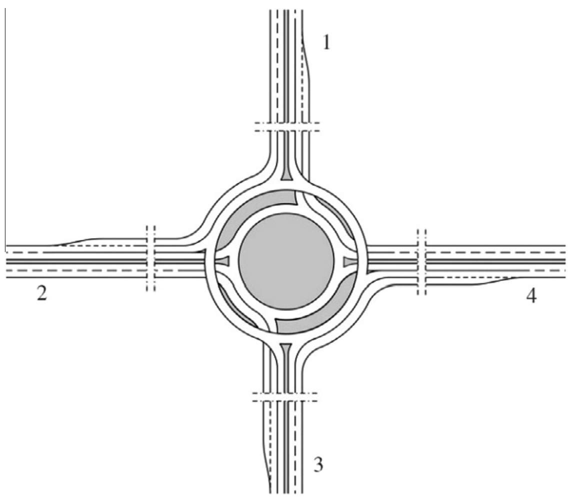

Fig. 1. Typical layout of a target roundabout; sketch.

lanes. The dual one-lane roundabout on two levels allows driving from all directions to all directions, and it "forgives errors", i.e. a driver who mistakenly stays at the entrance to the left-hand lane, can turn right at the next exit (differently from a turbo-roundabout).

By physically separating the right-turn traffic flow, dual one-lane roundabouts are obtained with no crossing conflict spots (unlike conventional two-lane or turbo-roundabouts), and no weaving conflict spots (unlike conventional two-lane roundabouts). When moving from the circulatory carriageway onto the road section, any possible weaving conflict spots are in front of a roundabout (as in turbo- and flower-roundabouts), which is a safer solution for improving traffic safety. A target roundabout has just 8 merging and 8 diverging conflict spots (Tollazzi et al., 2013) (as the dual one-lane roundabout) and actually a driving similar to a turbo-roundabout with the same traffic sign and road markings. Although a target roundabout is very useful within suburban areas, where large spaces allow implementing two-level interchanges (standard diamond, diverging diamond, cloverleaf interchange, etc.), this solution is fully acceptable in urban areas thanks to its small size.

Four-flyover roundabout

The roundabout with dedicated left-turn bypasses-on major roads, called "four-flyover roundabout" (Fig. 2), is designed as a large one-lane roundabout at upper level, and separate left-turn bypass lanes – located at a lower level – for both left-hand turners on the major roads; drivers are always situated at the left-hand lane on the approach as with conventional intersections.

By physically separating the left-turn traffic flow on major roads, a one-lane roundabout is obtained with no crossing conflict spots (unlike turbo-roundabouts), and no weaving conflict spots (unlike conventional two-lane roundabouts). When transferring from the circulatory carriageway onto the road section, any possible weaving conflict spots are in front of a roundabout (as with turbo-, flower- and target roundabouts), which is a safer solution for improving traffic safety. A four-flyover roundabout has just 6 merging and 6 diverging conflict spots (Tollazzi, 2014).

Capacity and delay estimation

Target roundabouts

In target roundabouts (Tollazzi et al., 2013; Tollazzi, 2014) circulating flows in front of each entry are lower than those at conventional, flower- and four-flyover roundabouts (see Table 1). Every entry of a target roundabout consists of two lanes:

(a) the former (*Lane 1*) dedicated to intersection crossing, left-turning and right-turning;
(b) the latter (*Lane 2*) dedicated to right-turning.

Entry capacity of every lane can be estimated by taking antagonist (or contrasting) flows and entry flows into account. For Lane 1 of any arm "i" the antagonist is the circulating flow ($C_{1,i} = f(Q_{c,i})$). Lane 2 is, as a matter of fact, a right-turn bypass lane

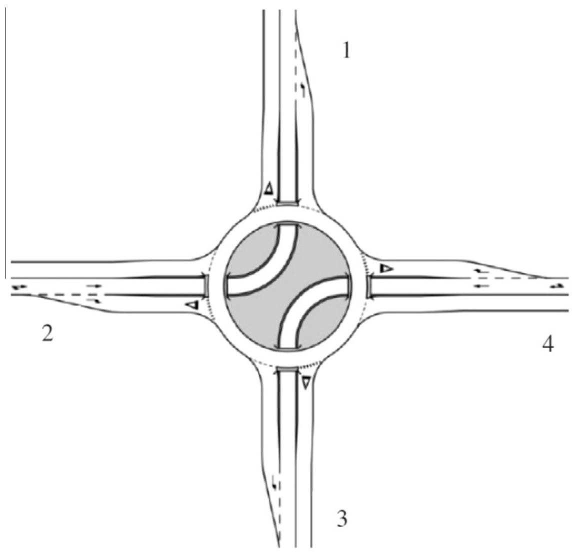

Fig. 2. Four-flyover roundabout; sketch.

Table 1
Circulating flows at roundabouts (the number of each arm is given in Fig. 1).

Roundabout Type	Target roundabout	Four-flyover roundabout	Conventional and flower-roundabouts
Circulating flows	$\begin{cases} Q_{c,1} = Q_{3,2} \\ Q_{c,2} = Q_{4,3} \\ Q_{c,3} = Q_{1,4} \\ Q_{c,4} = Q_{2,1} \end{cases}$	$\begin{cases} Q_{c,1} = Q_{3,2} + (Q_{4,2} + Q_{4,3}) \\ Q_{c,2} = (Q_{1,3} + Q_{1,4}) \\ Q_{c,3} = Q_{1,4} + (Q_{2,4} + Q_{2,1}) \\ Q_{c,4} = (Q_{3,1} + Q_{3,2}) \end{cases}$	$\begin{cases} Q_{c,1} = Q_{3,2} + (Q_{4,2} + Q_{4,3}) \\ Q_{c,2} = Q_{4,3} + (Q_{1,3} + Q_{1,4}) \\ Q_{c,3} = Q_{1,4} + (Q_{2,4} + Q_{2,1}) \\ Q_{c,4} = Q_{2,1} + (Q_{3,1} + Q_{3,2}) \end{cases}$

as its flow does not enter the ring carriageway; for entry "i" the contrasting flow is that coming out of the arm "i + 1" (($C_{2,i} = f(Q_{u,i+1})$) (Mauro and Guerrieri, 2013b).

Capacity laws used for analyzing this research are described below.

Capacity of Lane 1 (used for crossing and left-hand turning)

According to Brilon equation (Brilon et al., 1993; Brilon et al., 1997; Brilon, 2005) the entry lane capacity C_1 can be estimated by means of the following relation:

$$C_1 = 3600 \cdot \left(1 - \frac{t_{min} \cdot Q_{c,i}}{3600}\right) \cdot \frac{1}{t_f} \cdot e^{-\frac{Q_{c,i}}{3600}\left(t_g - \frac{t_f}{2} - t_{min}\right)} \tag{1}$$

where t_g is the critical gap [s]; t_f the follow-up time [s]; t_{min} the minimum gap between succeeding vehicles on the circle [s]. The behavioural parameters for entry capacity calculations according to Eq. (1) are given below as function of the inscribed circle diameter "d" [m]:

$$\begin{cases} t_g = 3.86 + \frac{8.27}{d} \\ t_f = 2.84 + \frac{2.07}{d} \\ t_{min} = 1.57 + \frac{18.6}{d} \end{cases} \tag{2}$$

The previous Eq. (1) highlights that capacity C_1 is influenced by circulating vehicles $Q_{c,i}$, by drivers' behaviours (through parameters t_g, t_f, t_{min}) and by the geometric characteristics of the intersection (i.e. inscribed circle diameter "d").

Fig. 3 shows the capacity laws relating to entry lanes, respectively for upper level roundabout (d = 90 m) and for lower level roundabout (d = 60 m) (see Fig. 1) at a target-roundabout.

Capacity of Lane 2 (used for right-hand turning)

Lane 2 for right-hand turning is a real bypass from a functional point of view. According to the type of traffic regulation, bypasses can be divided into (Al-Ghandour et al., 2012): (a) bypass with stop sign; (b) bypass with yield sign; c) free-flow bypass with an acceleration lane.

Design criteria for roundabout bypasses are provided for in *Czech Design Guidelines for Road Intersections*. The capacity law for these bypass types was obtained by Tracz et al. (2011) and by Mauro and Guerrieri (2013b). The analytical expressions are shown in Table 2 (Q_u stands for the contrasting flow). In this article Lane 2 was considered as free flowing.

Fig. 4 shows Lane 2 capacity values (C_2) for different types of traffic regulation (stop, yield and free-flow).

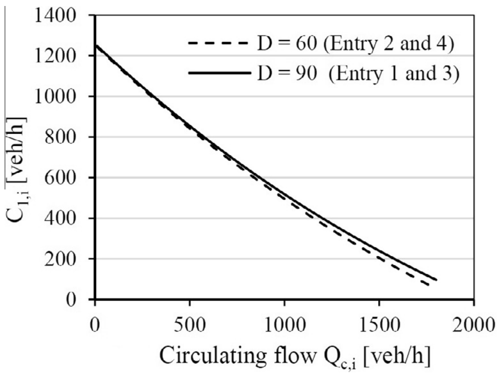

Fig. 3. Lane 1 entry capacity as function of circulating flow.

Table 2
Bypass lane capacity laws (Lane 2 capacity).

Bypass type	Capacity Law	
Bypass with stop sign	$C_2 = 1231{,}4 \cdot e^{-0{,}0012 \cdot Q_u}$	(3)
Right-turn yield bypass lane	$C_2 = 1130 \cdot e^{-0{,}001 \cdot Q_u}$	(4)
Free-flow bypass lane	$C_2 = 1250 \cdot e^{-0{,}0007 \cdot Q_u}$	(5)

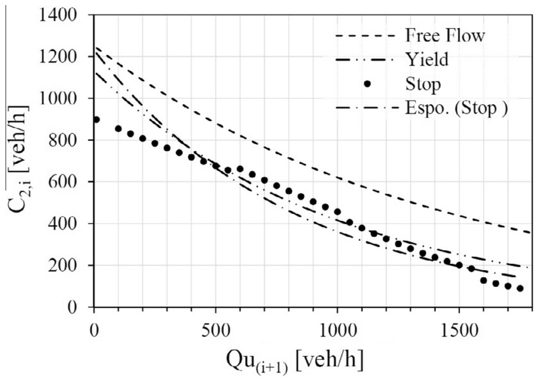

Fig. 4. Lane 2 capacity as function of exiting flow.

Entry capacity

Entry capacity C_i at entry "i" can be calculated by means of Eq. (6) considering the degree of saturation for Lane 1 and Lane 2 ($x_1 = Q_1/C_1$ and $x_2 = Q_2/C_2$) (Akcelik, 1997; Mauro and Branco, 2010; Mauro and Guerrieri, 2013b):

$$C_i = \frac{(Q_1 + Q_2)}{\max[x_1; x_2]} \tag{6}$$

where Q_1 and Q_2 denote respectively the flows on Lane 1 and Lane 2, at entry "i".

Fig. 5 shows the entry capacity as function of x_1, x_2, Q_c and Q_u.

Delay evaluation

For the aim of this research, vehicle delays in every lane were estimated through the following formulations in the HCM 2010:

$$D_1 = \frac{3600}{C_1} + 900T \cdot \left[\frac{Q_1}{C_1} - 1 + \sqrt{\left(\frac{Q_1}{C_1} - 1\right)^2 + \frac{\left(\frac{3600}{C_1}\right) \cdot \left(\frac{Q_1}{C_1}\right)}{450 \cdot T}}\right] + 5 \cdot \min\left[\frac{Q_1}{C_1}, 1\right] \tag{7}$$

$$D_2 = \frac{3600}{C_2} + 900 \cdot T \cdot \left[\frac{Q_2}{C_2} - 1 + \sqrt{\left(\frac{Q_2}{C_2} - 1\right)^2 + \frac{\left(\frac{3600}{C_2}\right) \cdot \left(\frac{Q_2}{C_2}\right)}{450 \cdot T}}\right] + 5 \cdot \min\left[\frac{Q_2}{C_2}, 1\right] \tag{8}$$

where D_1 = average control delay for Lane 1 [s/veh]; D_2 = average control delay for Lane 2 [s/veh]; T = reference time (h), (T = 1 for a 1-h analysis, T = 0.25 for a 15-min analysis. In the research we used T = 0.25).

Total average delay at entry "i" is expressed by the following equation (Mauro and Guerrieri, 2013b):

$$D_i = \frac{D_1 \cdot Q_1 + D_2 \cdot Q_2}{Q_1 + Q_2} \tag{9}$$

Similarly, the average delay of the intersection can be calculated with the weighted average of delays at each entry "i" (by using entry flow as weight). Delays can be associated to the corresponding level of service (HCM 2010).

Fig. 6 shows the entry average delay as function of x_1, x_2, Q_c and Q_u.

Four-flyover roundabout

In four-flyover roundabouts (Tollazzi, 2014) two arms, opposed to each other (arms Nos. 1 and 3 in Fig. 2), have an only entry lane while the other two arms (Nos. 2 and 4 in Fig. 2) have two entry lanes. The ring has a single lane. The circulating flow in front of each entry is shown in Table 1.

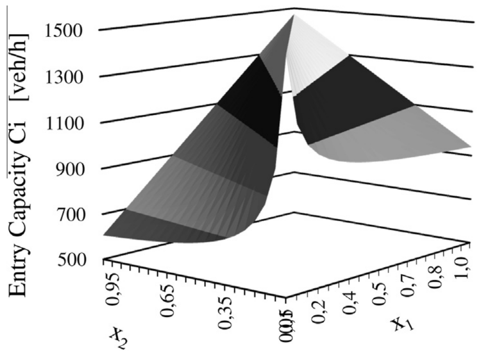

Fig. 5. Example of entry capacity C_i values at target roundabout (entry Nos. 2 and 4; Q_c = 700 veh/h Q_u = 450 veh/h).

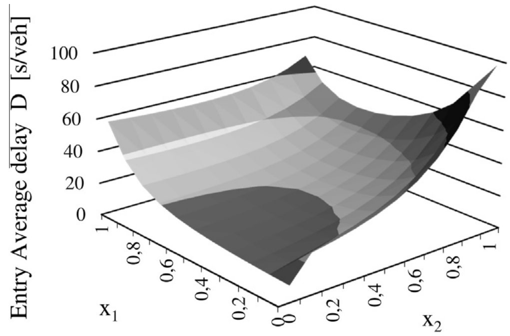

Fig. 6. Example of entry average delay D_i values at target roundabout (entry Nos. 2 and 4; Q_c = 700 veh/h Q_u = 450 veh/h).

As for arms Nos. 1 and 3, entry capacity C_i can be estimated by applying the HCM 2010 formula concerning roundabouts with one lane at entries and one at the ring:

$$C_i = 1130 \cdot e^{-0{,}001 \cdot Q_u} \tag{10}$$

Arms Nos. 2 and 4 (Fig. 3) have two dedicated entry lanes, i.e.

- the former (Lane 1) only for the left-hand turning. This lane does not enter the ring carriageway but merges directly into the destination arm thanks to two subways. The left-turn flow is free, i.e. it is not contrasted by other flows;
- the latter (Lane 2), used only for crossing, right turning and left-turning (on the same level).

Capacity of Lane 1 (used for left-hand turning)

Considering that the lane is free flowing (i.e. there is no contrasting flow) and no empirical data is available, we can assume Lane 1 capacity as constant (Mauro and Guerrieri, 2013b; Tracz et al., 2011):

$$C_1 = 1250 \text{ veh/h} \tag{11}$$

Capacity of Lane 2 (used for crossing and right-hand turning)

On the capacity estimation of this lane we can make the same observations as Eq. (10); it thus follows

$$C_2 = 1130 \cdot e^{-0{,}001 \cdot Q_u} \tag{12}$$

Entry capacity and delay

Entry capacity and delay were estimated by means of the general Eqs. (6)–(9), already described for target roundabouts.

Flower and Conventional Roundabouts

For the aim of this research, the at-grade roundabout (one-level intersection) was analyzed by means of models already available in the literature (NCHRP Report 672, 2010).

Especially for flower roundabouts (with a bypass lane controlled by stop or yield signs, or free flowing) the analysis was carried out with the method by Corriere et al. (2013). For conventional roundabouts we used the formulations in the Highway Capacity Manual (2010).

Functional analysis

Target and four-flyover roundabouts were compared with conventional and flower roundabouts in terms of performances. We considered eight geometric layouts altogether:

1. Target roundabout
2. Four flyover roundabout
3. Flower roundabout with right-turn bypass lane with stop sign (Flower-Stop)
4. Flower roundabout with right-turn bypass lane with yield sign (Flower-Yield)
5. Flower roundabout with free-flow right-turn bypass lane (Flower-Free)
6. Conventional with an entry lane and a ring lane (1 + 1)
7. Conventional with an entry lane and two ring lanes (1 + 2)
8. Conventional with two entry lanes and two ring lanes (2 + 2).

A great number of traffic simulations were run by considering three traffic distribution matrices ρ1, ρ2 and ρ3 (Table 3), and total entry arm flows ranging between 200 and 4800 veh/h and equally distributed among the four arms of each intersection.

Such matrices allowed examining three clearly distinct limit conditions of traffic flow distribution, i.e.

– Matrix ρ1 = 70% of vehicles turn right, 15% cross and 15% turn left;
– Matrix ρ2 = 15% of vehicles turn right, 70% cross, 15% turn left;
– Matrix ρ3 = 15% of vehicles turn right, 15% cross, 70 % turn left.

By means of the capacity models previously described, we obtained capacity values, saturation degrees, delays and levels of service for each lane, arm and entire intersection in the aforesaid traffic conditions. Especially Figs. 7–9 show average delays at intersections in function of total traffic demand (a delay higher than or equal to 50 s/veh corresponds to a level of service F (LOS F)).

We can clearly see that a target roundabout causes lower delays in all traffic conditions, irrespective of the distribution (ρ) and flow intensity.

Higher capacity values, and consequently lower delays, for all the intersections occur when most of the entry flow turns right, or in case of Matrix ρ1. In this specific traffic distribution condition, all the circulating flows ($Q_{c,i}$) in front of roundabout entries are – entry flows being equal – lower than those occurring with distributions ρ2 and ρ3, ($Q_{c,i}(\rho1) < Q_{c,i}(\rho2) < Q_{c,i}(\rho3)$). And indeed, graphs in Figs. 7–9 show that delays increase when moving from condition ρ1 to condition ρ2 and finally to ρ3, entry flow being equal.

As evident from analyzing such figures, a four-flyover roundabout does not give good performances only when the right-turn flow is extremely high (ρ1); and, as a matter of fact, this intersection should be used when the left turning manoeuvre prevails (as happens in the case of Matrix ρ3).

With reference to at-grade intersections, conventional roundabouts (2 + 2) provide higher capacity and lower delays than other conventional roundabouts ((1 + 1) and (1 + 2)).

Flower-roundabouts, in any type of bypass lane regulation, are always more convenient than roundabouts (1 + 1) and, moreover, with elevated right-turning flows they cause delays similar to those generated by roundabouts (2 + 2). It is then known that in any case free-flow bypasses determine lower average delays at intersections compared to those likely to be found in bypasses with stop or yield signs (Mauro and Guerrieri, 2013b).

Degrees of saturation x were measured for each lane of every intersection (flow/capacity ratio). Moreover we determined the law which correlates the saturation degree of the most critical lane x^* of every intersection ($x^* = \max(x_1; x_2; \ldots x_m)$ where m is the total number of entry lanes assessed along the entire intersection) with the total entry flow.

Quite interestingly, in all cases examined the trend line which best approximates the relationship between saturation degree of the critical lane and total entry flow is a polynomial curve of second order, with the exception of target

Table 3
O/D Matrices – origin/destination matrices of traffic flows in percentage terms (the arm numeration is illustrated in Fig. 1).

O/D matrices

$$\rho1 = \begin{vmatrix} 0 & 0.7 & 0.15 & 0.15 \\ 0.15 & 0 & 0.7 & 0.15 \\ 0.15 & 0.15 & 0 & 0.7 \\ 0.7 & 0.15 & 0.15 & 0 \end{vmatrix} \quad \rho2 = \begin{vmatrix} 0 & 0.15 & 0.7 & 0.15 \\ 0.15 & 0 & 0.15 & 0.7 \\ 0.7 & 0.15 & 0 & 0.15 \\ 0.15 & 0.7 & 0.15 & 0 \end{vmatrix} \quad \rho3 = \begin{vmatrix} 0 & 0.15 & 0.15 & 0.7 \\ 0.7 & 0 & 0.15 & 0.15 \\ 0.15 & 0.7 & 0 & 0.15 \\ 0.15 & 0.15 & 0.7 & 0 \end{vmatrix}$$

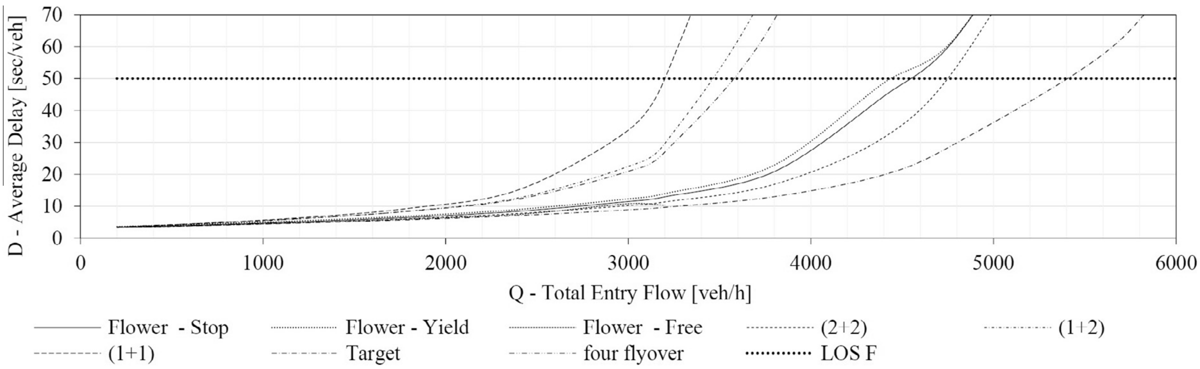

Fig. 7. Average delay for ρ1 Matrix.

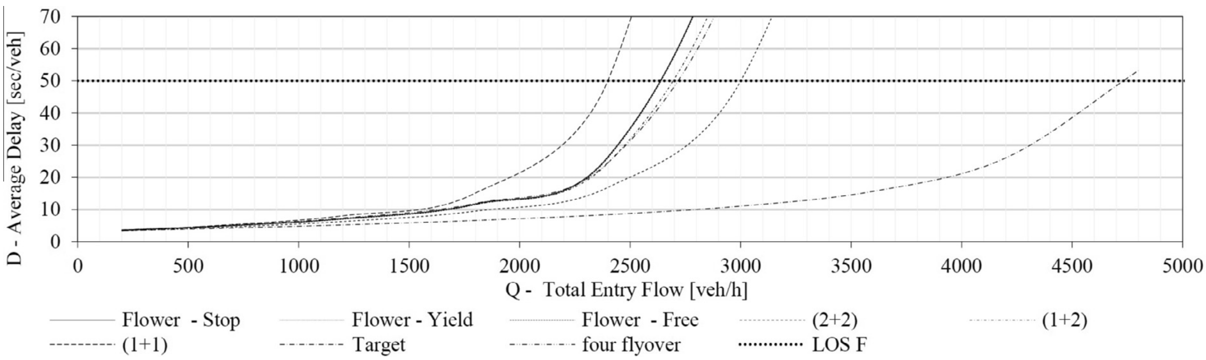

Fig. 8. Average delay for ρ2 Matrix.

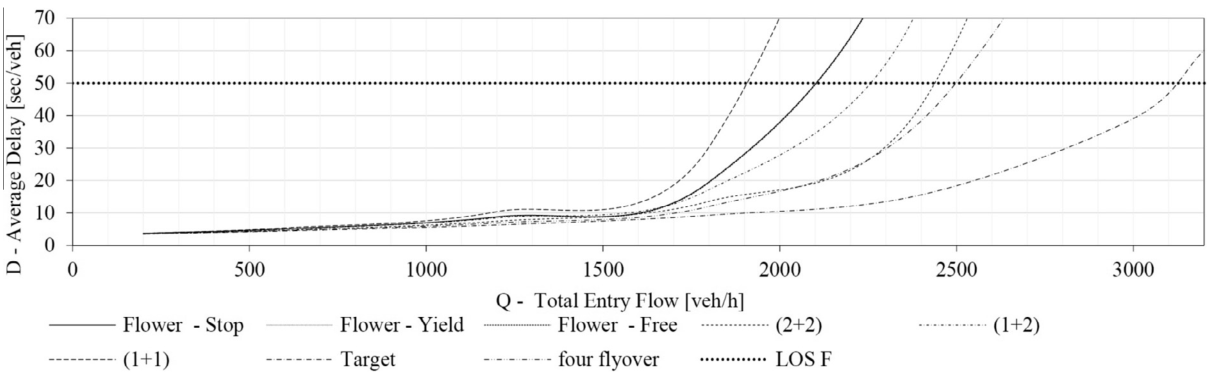

Fig. 9. Average delay for ρ3 Matrix.

roundabouts where the relationship providing the maximum R^2 is a straight line (see, for instance, Fig. 10 obtained from Matrix ρ2).

Pollutant emission estimation

When selecting an optimal type of intersection, environmental criteria are now to be considered extremely important along with the others (e.g. functional, spatial, capacity, traffic safety).

As a general rule roundabouts provide environmental benefits by reducing vehicle delays and the number and duration of stops, compared with traffic signal-controlled intersections. On roundabouts, even in case of large volumes, vehicles move slowly in queues rather than come to a complete halt.

This reduces the number of acceleration/deceleration cycles and time spent idling and, consequently, air quality impact and fuel consumption in a significant manner (Mandavilli et al., 2008; Gokhale, 2012; Al-Ghandour, 2013).

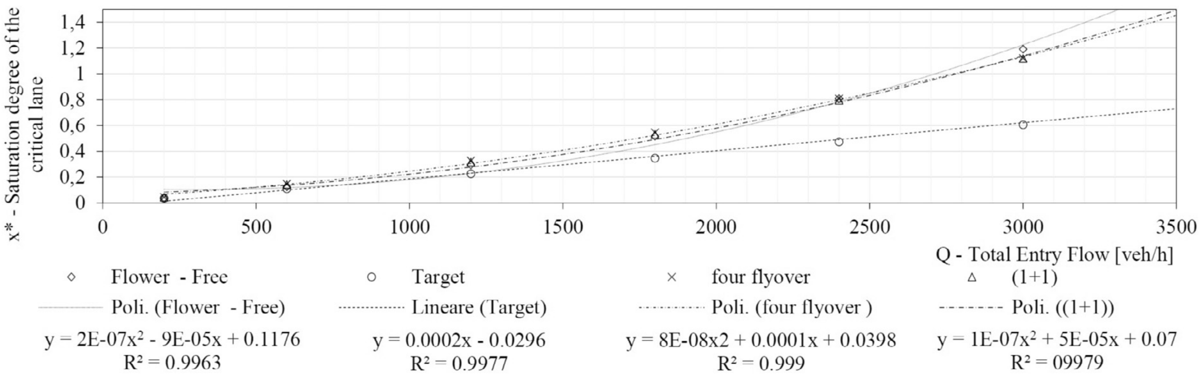

Fig. 10. Saturation degree of the critical lane (ρ2 Matrix).

According to several authors exhaust emissions increase by few percentages for CO and NO_x when a priority intersection is replaced by a one-lane roundabout, and they decrease by approximately thirty percentages for carbon monoxide CO and approximately twenty percentages for nitrogen oxide NO_x if signalized intersection is replaced by a one-lane roundabout (Tollazzi, 2014).

In order to explain the potential benefits of target and four-flyover roundabouts, compared to conventional layouts, with regard to pollutant emissions, we used the COPERT 4 software (Gkatzoflias et al., 2011) in several traffic conditions previously dealt with.

COPERT 4 is a software tool used worldwide to calculate air pollutant and greenhouse gas emissions from road transport. The development of COPERT is coordinated by the European Environment Agency (EEA), in the framework of the activities of the European Topic Centre for Air Pollution and Climate Change Mitigation. The European Commission's Joint Research Centre manages the scientific development of the model (Yu et al., 2013).

The CORINAIR model, implemented in the COPERT 4, takes into account many traffic parameters like vehicle types, categories and population, yearly mileage (km/year), mean fleet mileage (km). The methodology allows calculating the exhaust emissions of carbon monoxide, nitrogen oxides, non-methane volatile organic compounds, methane, particulate matter, carbon dioxide and many others. The emission factor (EF) for each exhaust emission and for each transport modality m is calculated by means of the following equation:

$$EF^m_{\lambda jk} = RF \cdot K \ [g/km] \tag{13}$$

$$EF^m_{\lambda jk} = RF \cdot \begin{cases} a^m_{\lambda jk} + b^m_{\lambda jk}v + d^m_{\lambda jk}v^2 & f = 1 \\ a^m_{\lambda jk} \cdot v^{b^m_{ijk}} & f = 2 \\ a^m_{\lambda jk} \cdot e^{b^m_{ijk} \cdot v} & f = 3 \\ a^m_{\lambda jk} + b^m_{\lambda jk} \cdot \ln(v) & f = 4 \end{cases} \tag{14}$$

where λ index is fuel type; J index is vehicle age; K is engine displacement volume; m transportation mode; a, b, d are three parameters correlated to single pollutant emissions; f depends on pollutant type; RF is a reduction function of emitting classes.

Total emissions Eγ for pollutant "i" can thus be calculated as:

$$E_\gamma = EF_i \cdot N_i \cdot \overline{p_i} \quad [g/year] \tag{15}$$

where $\overline{p_i}$ is the average annual trip length [km] and N_i is the annual number of vehicles belonging to the same emission group. The method also allows to consider the effect of hot and cold emissions as well as some specific infrastructure characteristics (i.e. longitudinal gradient) and the road context (urban, rural, headway), etc.

Functional, environmental and economic analysis: comparison of different layouts

The aims of the research were capacity analysis, delay estimation and calculation of CO_2, $PM_{2.5}$, PM_{10}, NO_x pollutant emissions for 8 different 4-arm roundabouts (see Section Functional analysis).

The examined traffic demand curve is shown in Fig. 11; the maximum hourly traffic (Q_{max}) per year varied in the interval Q_{max} = 1300 ÷ 3300 veh/h. The traffic distribution test matrix considered is ρ2 (see Table 3).

In function of the demand curve in Fig. 11, when Q_{max} = 1300 ÷ 3300 veh/h varies, we can obtain the total delays accumulated by users in a year (D) for a given traffic distribution defined by ρ2, by means of the expression (Mauro and Cattani, 2012):

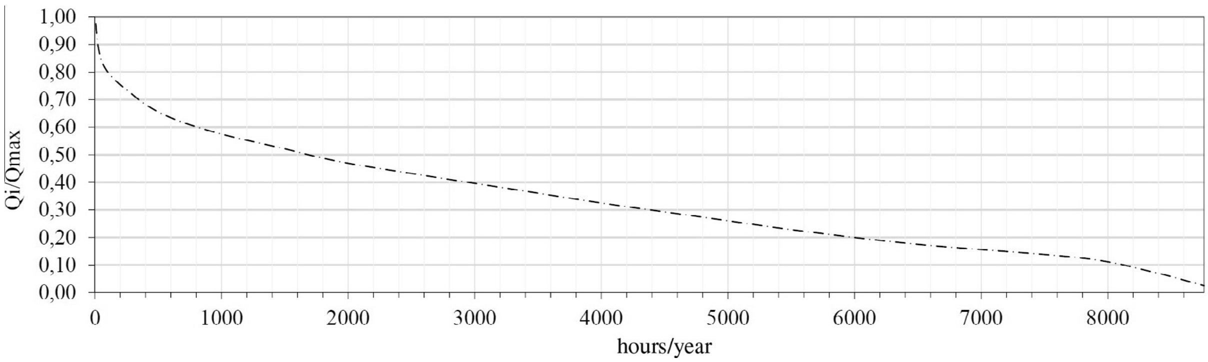

Fig. 11. Traffic demand curve (suburban context).

$$D = \sum_i [d(Q_i) \cdot T(Q_i) \cdot Q_i] \tag{16}$$

where Q_i [veh/h] is every traffic flow reference value; $d(Q_i)$ [s] is the average delay associated with a total flow Q_i; $T(Q_i)$ [s] is the hour amount per year for the observed flow equal to Q_i.

The traffic demand curve in Fig. 11 was considered to apply Eq. (16). On the basis of the annual peak flow, we examined 20 Q_i intervals ($0.025\ Q_{max} \leqslant Q_i \leqslant 0.975\ Q_{max}$); we estimated the hour amount per year $T(Q_i)$ for each Q_i value, and also the average delay at intersections. By applying Eq. (15) the annual total delay was then obtained for each layout in question. The procedure was replicated for intervals of annual peak flows in the range $Q_{max} = 1300 \div 3300$ veh/h (the considered increment intervals were equal to 100 veh/h).

Figs. 12–14 show delays accumulated as the total flow entering the roundabout varies $Q_{max} = 1300$ veh/h, $Q_{max} = 2300$ veh/h and $Q_{max} = 3300$ veh/h respectively.

It is worth underlining that when the maximum hourly traffic (Q_{max}) is moderate, annual delays at intersections have values very close to each other. In this case (e.g. $Q_{max} = 1300$ veh/h, see Fig. 12), although the target roundabout certainly provides the best performances, its highest construction costs do not justify its implementation, as explained below.

As Q_{max} increases, the differential between delays at intersections increases as well. For instance, for $Q_{max} = 3300$ veh/h and a flow value of 2500 veh/h entering the roundabout, the annual delay of a conventional roundabout (1 + 1) is over 16,000,000 s, while in a target roundabout it is around 2,000,000 s (around 1/8).

Pollutant emissions were estimated in a neighbourhood of 0.5 km away from the intersection, by assuming a free-flow speed (FFS) of 50 km/h (value of the most common speed limit in urban context of several European countries). Entry speeds to the ring and speeds at intersection exits were determined in function of the path radius "R" and superelevation "e" by applying the criteria reported in the AASHTO "Green Book" 2011 (AASHTO, 2011). In estimating the average speed (which takes the phases of deceleration, intersection length and acceleration into account) we considered delays as well (see Figs 7–9 and Figs. 12–14).

We examined nine different vehicle types (light, heavy-duty, petrol- or diesel-fuelled), distributed as shown in Table 4.

With the aid of the COPERT software we determined emissions at intersections as the annual traffic Q_{TOT} (obtained on the basis of the demand curve in Fig. 10 and Q_{max}) changed, with percentage distribution of Matrix ρ2 flows. Results are given in Tables 5–8.

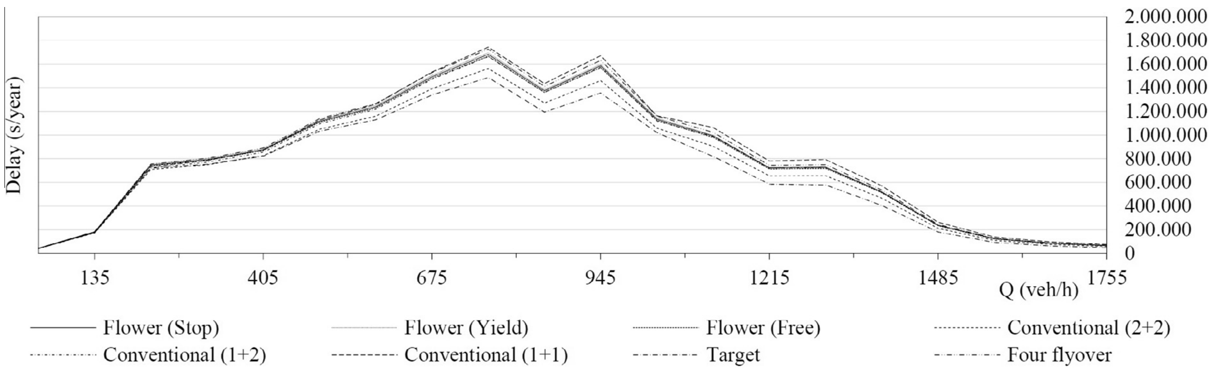

Fig. 12. Annual delays as function of total entry flow (ρ2; Q_{max} = 1300 veh/h).

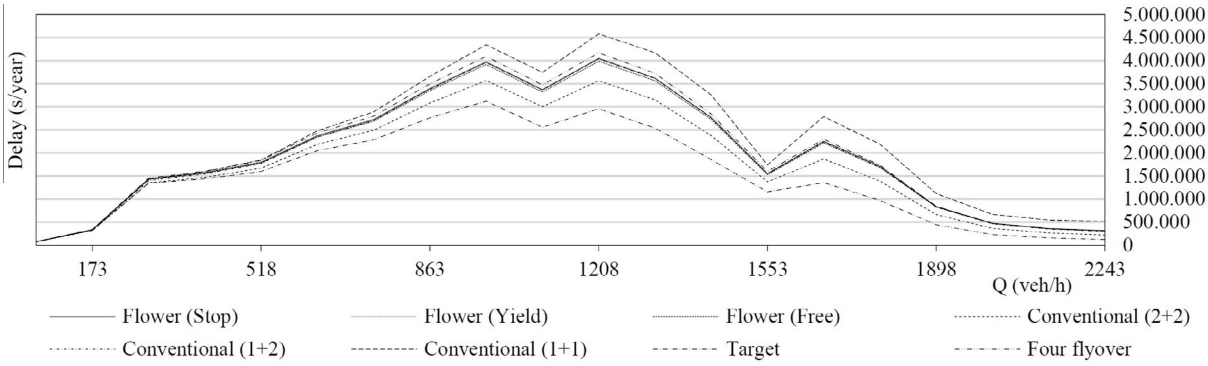

Fig. 13. Annual delays as function of total entry flow (ρ2; Q_{max} = 2300 veh/h).

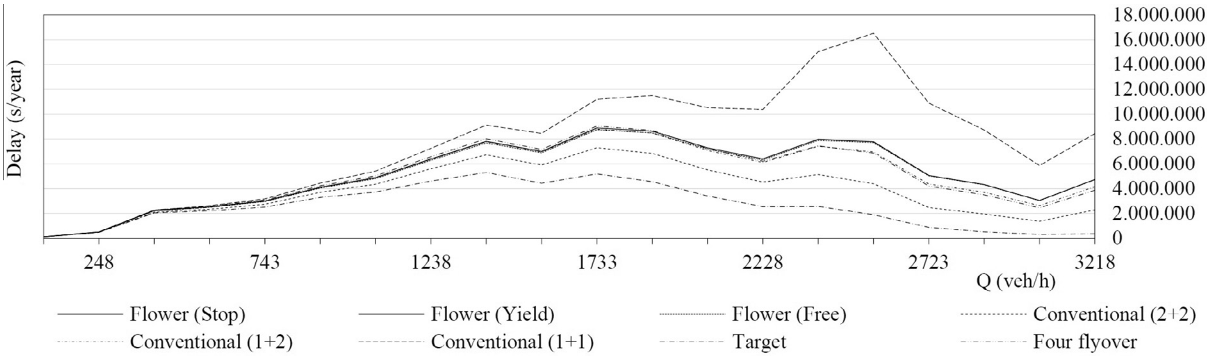

Fig. 14. Annual delays as function of total entry flow (ρ2; Q_{max} = 3300 veh/h).

Once vehicle delays and emissions were obtained, we evaluated the total costs attributable to the layouts in question. To this end, we considered the following construction costs (BC_k) (Mauro and Cattani, 2012):

1. Target-roundabout = €3,980,000
2. Four-flyover roundabout = €2,050,000
3. Flower-roundabout with right-turn bypass lane with stop sign (Flower-Stop) = €1,200,000
4. Flower-roundabout with right-turn bypass lane with yield sign (Flower-Yield) = €1,200,000
5. Flower-roundabout with free-flow right-turn bypass lane (Flower-Free) = €1,600,000
6. Conventional with an entry lane and a ring lane (1 + 1) = €1,050,000
7. Conventional with an entry lane and two ring lanes (1 + 2) = €1,120,000
8. Conventional with two entry lanes and two ring lanes (2 + 2) = €1,300,000

For all types of intersection, except for the target roundabout, we assumed annual management costs as equal to €10,000 per year. For a target roundabout we assumed €20,000 per year.

As regards unit costs due to pollutant emissions, we attributed the following values ($C_{E\gamma}$): CO_2 = 0.04 €/kg; NO_x = 0.0044 €/g; $PM_{2.5}$ = 0.087 €/g; and PM_{10} = 0.087 €/g, in accordance with the EU Directive 2009/33/EC.

Table 4
Vehicle types considered in the study.

Passenger cars [veh/year]						Heavy Duty Trucks [veh/year]			Q_{TOT} [veh/year]	Q_{max} [veh/h]
Petrol EURO 2	Petrol EURO 3	Petrol EURO 4	Diesel EURO 2	Diesel EURO 3	Diesel EURO 4	Diesel EURO 2	Diesel EURO 3	Diesel EURO 4		
582,865	349,509	752,385	196,691	430,048	806,727	86,617	86,617	173,235	3,464,695	1300
807,044	483,935	1,041,764	272,342	595,451	1,117,007	119,932	119,932	239,864	4,797,270	1800
1,031,223	618,362	1,331,143	347,992	760,854	1,427,287	153,246	153,246	306,492	6,129,845	2300
1,255,402	752,788	1,620,522	423,643	926,256	1,737,567	186,561	186,561	373,121	7,462,420	2800
1,479,581	887,214	1,909,901	499,293	1,091,659	2,047,847	219,875	219,875	439,750	8,794,995	3300

Table 5
CO_2 emissions at roundabout intersections.

CO_2 emissions [t/year]									
Annual Traffic	Qmax [v/h]	Flower (Stop)	Flower (Yield)	Flower (Free)	Conventional (2 + 2)	Conventional (1 + 2)	Conventional (1 + 1)	Target	Four flyover
3,464,695	1300	735	734	734	733	734	735	733	735
4,797,270	1800	947	947	947	945	947	948	943	947
6,129,845	2300	1214	1215	1214	1211	1214	1218	1207	1215
7,462,420	2800	1477	1477	1477	1481	1488	1502	1472	1490
8,794,995	3300	1780	1780	1779	1759	1775	1822	1739	1777

Table 6
NO_x emissions at roundabout intersections.

NOx Emissions [t/year]									
Annual Traffic	Qmax [v/h]	Flower (Stop)	Flower (Yield)	Flower (Free)	Conventional (2 + 2)	Conventional (1 + 2)	Conventional (1 + 1)	Target	Four flyover
3,464,695	1300	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
4,797,270	1800	2.68	2.68	2.68	2.68	2.68	2.68	2.67	2.66
6,129,845	2300	3.44	3.44	3.43	3.43	3.44	3.44	3.42	3.44
7,462,420	2800	4.18	4.18	4.18	4.19	4.20	4.24	4.17	4.21
8,794,995	3300	5.02	5.02	5.01	4.97	5.00	5.11	4.92	5.01

Table 7
$PM_{2.5}$ emissions at roundabout intersections.

$PM_{2.5}$ Emissions [t/year]									
Annual Traffic	Qmax [v/h]	Flower (Stop)	Flower (Yield)	Flower (Free)	Conventional (2 + 2)	Conventional (1 + 2)	Conventional (1 + 1)	Target	Four flyover
3,464,695	1300	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14
4,797,270	1800	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19
6,129,845	2300	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24
7,462,420	2800	0.29	0.29	0.29	0.29	0.29	0.30	0.29	0.30
8,794,995	3300	0.35	0.35	0.35	0.35	0.35	0.36	0.34	0.35

Table 8
PM_{10} emissions at roundabout intersections.

PM_{10} Emissions [t/year]									
Annual Traffic	Qmax [v/h]	Flower (Stop)	Flower (Yield)	Flower (Free)	Conventional (2 + 2)	Conventional (1 + 2)	Conventional (1 + 1)	Target	Four flyover
3,464,695	1300	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18
4,797,270	1800	0.32	0.32	0.32	0.31	0.31	0.31	0.31	0.32
6,129,845	2300	0.32	0.32	0.32	0.31	0.31	0.31	0.31	0.32
7,462,420	2800	0.38	0.38	0.38	0.39	0.39	0.39	0.38	0.39
8,794,995	3300	0.47	0.47	0.47	0.46	0.46	0.47	0.45	0.46

By way of example, Fig. 15 shows environmental costs of CO_2, NO_x, $PM_{2.5}$ and PM_{10} emissions in a target roundabout as Q_{max} varies.

For vehicle delays we considered a unit cost variable in the range $C_d = 20$ €/h ÷ 30 €/h.

Should the increase in annual road traffic be negligible and the unit costs of vehicle delays, fuel and pollutant emissions appear constant, the actualized total cost referring to N = 30 operational years for each examined intersection "j", was obtained by the following relation:

$$C_j^{TOT} = BC_K + \left[\sum_{T=1}^{N} \left(\sum_i [d(Q_i) \cdot T(Q_i) \cdot Q_i] \cdot C_d + E_\gamma \cdot C_{E_\gamma} \right)_T \right] \Big/ (1 + r)^T \tag{17}$$

By considering a discount rate r = 1.5 % in relation (17), we obtained the values shown in Figs. 16 and 17.

These graphs are suitable to choose the best roundabout intersection on economic grounds, while generally the criteria used are only based on intersection functionalities. The analysis makes a 30-year projection period, and thus total cost values

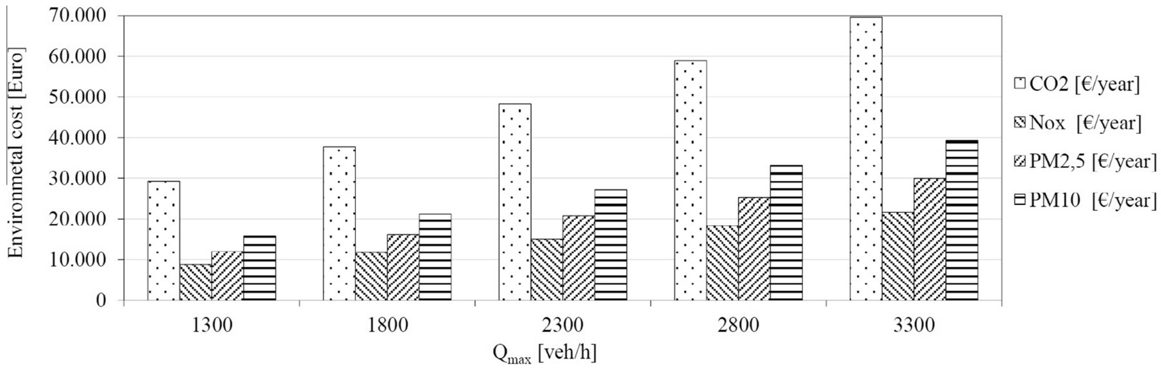

Fig. 15. Environmental costs for the target roundabout.

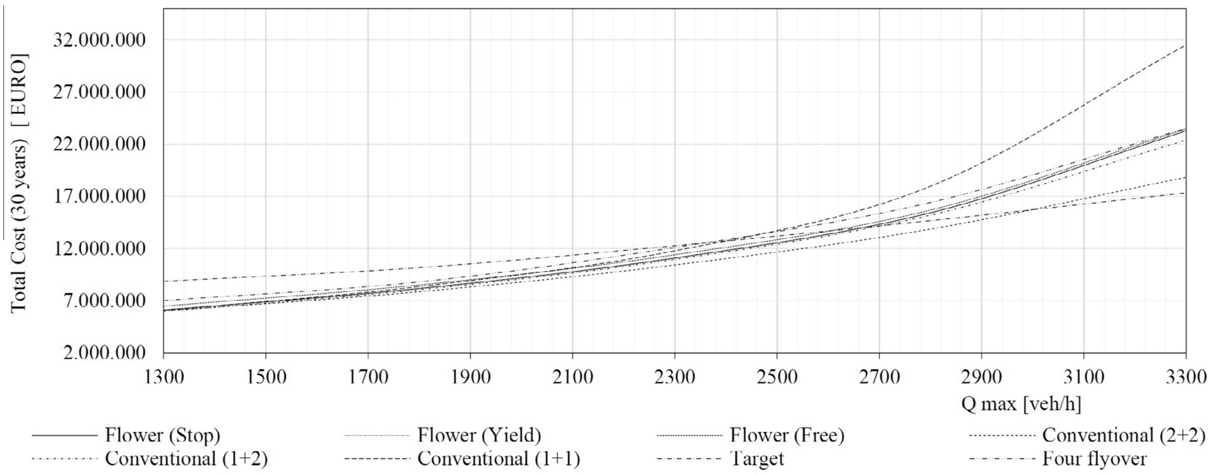

Fig. 16. Total cost (C_d = 20 €/h).

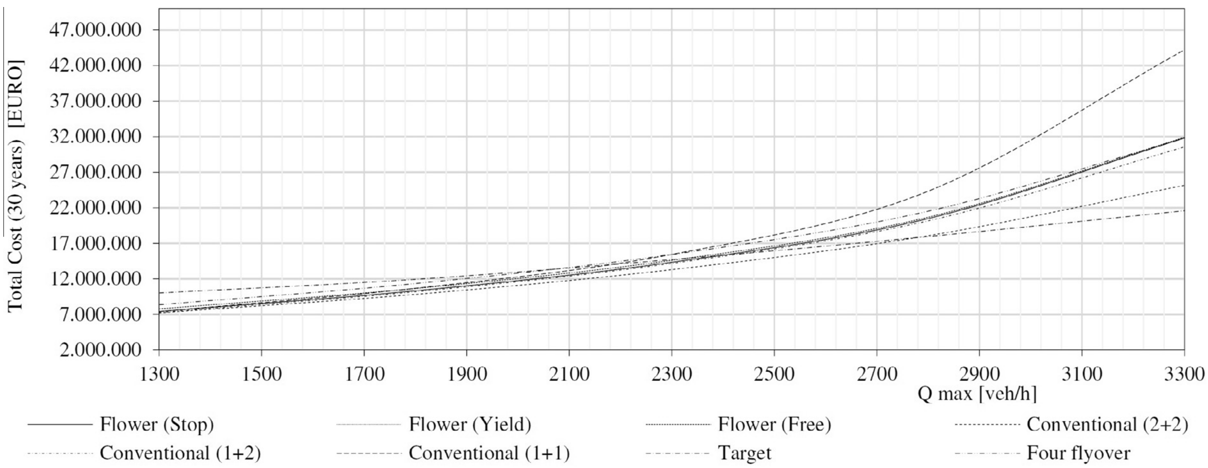

Fig. 17. Total cost (C_d = 30 €/h).

may be lightly overestimated seen that there will be less and less polluting vehicles in future and therefore more and more decreasing environmental costs, despite traffic conditions being the same.

Moreover, also the cost of delay (currently assessable at 20 €/h) may be modified somehow but, being correlated to GPD of a given country, it is quite difficult to foresee. This is also the reason why two different scenarios were considered and compared, the former with C_d = 20 €/h (Fig. 16) and the latter with C_d = 30 €/h (Fig. 17).

It is absolutely clear that target-roundabouts are not suited for moderate flows but rather they are very appropriate for medium-high entry traffic volumes (Q_{max} = 2800–3000 veh/h). Compared to the other intersections, the economic benefit from target roundabouts is increasingly higher with annual peak capacity over 3300 veh/h.

Conclusion

This research compares different roundabout intersections: target, four-flyer, flower and conventional roundabouts. We examined eight different geometric layouts altogether: 2 layouts on two-levels (target and four-flyer roundabouts) and 6 at-grade roundabouts.

We made functional and environmental comparisons: the former in terms of capacity and vehicle delays, the latter with regard to CO_2, NO_x, $PM_{2.5}$ and PM_{10} emissions.

Firstly, we presented a closed-form model for estimating capacity, delays and levels of service (LOS) of target and four-flyover roundabouts, recently designed in Slovenia. For flower- and conventional roundabouts we used calculation models very well known in the literature.

The functional comparison was made under numerous traffic conditions. Notably, three traffic distribution test matrices ρ1, ρ2, ρ3 were considered to identify as many limit situations: in the first, 70% of traffic coming from every arm turned right; in the second, 70% of entry traffic crossed the intersection, and in the third, 70% of traffic turned left.

At first we observed that there was an increase in vehicle delays moving from condition ρ1–ρ2 and finally to ρ3, with the same total flow at intersections. This was due to the gradual increase in circulating flows in front of entries ($Q_{c,i}(\rho1) < Q_{c,i}(\rho2)$ $Q_{c,i}(\rho3)$). The results of the analyses show that target roundabouts produce lower delays irrespective of traffic distribution (ρ) and flow intensity.

As regards four-flyover roundabouts, they result to be more suitable when left-turning manoeuvre prevails (as happens in Matrix ρ3).

As well known, among at-grade intersections, conventional roundabouts (2 + 2) have greater capacity and lower delays. On the other hand, flower roundabouts are always much more convenient than roundabouts (1 + 1), and in addition they lead to similar delays to those generated by roundabouts (2 + 2) with elevated right-hand turning flows.

In studying these intersections, we also investigated their total costs due to the following elementary expenditure items: (a) construction costs; (b) management costs; (c) delay costs; (d) environmental costs.

To this end, we considered a typical traffic demand curve (in a suburban context), the percentage traffic distribution ρ2 and an annual peak flow in the range Q_{max} = 1300 ÷ 3300 veh/h. We then determined annual pollutant emissions and accumulated delays as the entry traffic varied.

In order to estimate vehicle emissions we used the CORINAIR model implemented in the COPERT software for 9 different types of vehicles. Total costs were calculated over a 30-year operational lifetime.

Compared to the other intersections examined, the target roundabout has higher construction but lower delay and environmental costs. Thus, if we look at total costs, they are not very suited for medium-low traffic lows. On the other hand, target roundabouts are very advantageous with medium-high entry traffic volumes (Q_{max} = 2800–3000 veh/h). Their economic advantage is increasingly significant in annual peak flows higher than Q_{max} = 3300 veh/h.

References

AASHTO, 2011. A Policy on Geometric Design of Highways and Streets, sixth ed., (commonly referred to as the "Green Book").
Akcelik, R., 1997. Lane-by-lane modelling of unequal lane use and flares at roundabouts and signalised intersections: the SIDRA Solution. Traffic Eng. Control London 38 (7/8).
Al-Ghandour, M., Schroeder, B., Rasdorf, W., Delay Williams, B., 2012. Analysis of single-lane roundabout with a slip lane under varying exit types, experimental balanced traffic volumes, and pedestrians, using microsimulation. Transp. Res. Rec., 76–85.
Al-Ghandour, M., 2013. Experimental analysis of single-lane roundabout slip lanes: Fuel consumption and emissions. Green Streets, Highways, and Development 2013: Advancing the Practice – Proceedings of the 2nd Green Streets, Highways, and Development Conference, pp. 240–250.
Brilon, W., Stuwe, B., Drews, O., 1993. Sicherheit und Leistungs fähigkeit von Kreisverkehrsplätzen. Institute for Traffic Engineering, Ruhr Universität, Bochum (Deutschland).
Brilon, W., Bondzio, L. Wu, M., 1997. Unsignalized Intersection in Germany. A State of the Art. 2nd International Symposium for unsignalized intersection, Portland/Oregon (USA).
Brilon, W., 2005. Roundabouts: A State of the Art in Germany, National Roundabout Conference, (USA).
Corriere, F., Guerrieri, M., Ticali, D., Messineo, A., 2013. Estimation of air pollutant emissions in flower roundabouts and in conventional roundabouts. Arch. Civil Eng. 59 (2), 229–246. http://dx.doi.org/10.2478/ace-2013-0012.
Coelho, M.C., Farias, T.L., Rouphail, N.M., 2006. Effect of roundabout operations on pollutant emissions. Transp. Res. Part D Transp. Environ. 11 (5), 333–343.
Coelho, M.C., Fontes, T., Bandeira, J.M., Pereira, S.R., Tchepel, O., Dias, D., Sá, E., Amorim, J.H., Borrego, C., 2014. Assessment of potential improvements on regional air quality modelling related with implementation of a detailed methodology for traffic emission estimation. (2014). Sci. Total Environ. 470–471, 127–137.
CROW, 2008. Turborotondes, Publicatie 257. Dutch Information and Technology Platform, The Netherlands.
Czech Design Guidelines for Road Intersections, 2001. "Wytyczne Projektowania Skrzyzowan Drogowych, Czesc II", Warszawa.
Fortuijn, L.G.H., 2009. Turbo roundabouts: design principles and safety performance. Transportation Research Record: Journal of the Transportation Research Board, Transportation Research Board 2096, 16–24. http://dx.doi.org/10.3141/2096-03.
Gokhale, S., 2012. Impacts of traffic-flows on vehicular-exhaust emissions at traffic junctions. Transp. Res. Part D 17, 21–27.

Gkatzoflias, D., Kouridis, C., Ntziachristos, L., 2011. Description of new elements in COPERT 4 v 9,0, EMISIA SA Report, No: 11, RE,005, V1.

Guerrieri, M., Corriere, F., 2014. Estimation of measures of effectiveness (MOE) for the C-Roundabouts. Applied Mechanics and Materials, Volume 459 (2014), Trans Tech Publications, Switzerland, ISSN: 1660-9336, ISSN web 1662-7482, pp. 569–574. doi: 10.4028/www.scientific.net/AMM.459.569.

Guerrieri, M., Corriere, F., Parla, G., Di Vincenzo, D., Messineo, A., 2014. Reducing air pollutants through road innovative intersections. Appl. Mech. Mater. 459, 563–568. http://dx.doi.org/10.4028/www.scientific.net/AMM.459.563.

Highway Capacity Manual 2010, (HCM2010). Transportation Research Board.

Mandavilli, S., Rys, M.J., Russell, E.R., 2008. Environmental impact of modern roundabouts. Int. J. Ind. Ergonom. 38, 135–142.

Mauro, R., Cattani, M., 2004. Model to evaluate potential accident rate at roundabouts. J. Transp. Eng. 130 (5), 602–609.

Mauro, R., Branco, F., 2010. Comparative Analysis of Compact Multilane Roundabouts and Turbo-Roundabouts. J. Transp. Eng. ASCE 136 (4), 316–322, 1061, 10/(ASCE)TE,1943-5436,0,000,106.

Mauro, R., Branco, F., 2012. Two vehicular headways time dichotomic models. Modern Appl. Sci. 6 (12), 1–12.

Mauro, R., 2010. Calculation of Roundabouts: Capacity, Waiting Phenomena and Reliability. Springer-Verlag, Berlin Heidelberg.

Mauro, R., Cattani, M., 2012. Functional and economic evaluations for choosing road intersection layout. Promet Traffic Transp. 24 (5), 441–448, 10,7307/ptt, v24i5,1180.

Mauro, R., Guerrieri, M., 2013a. Flower roundabouts: performances analysis and comparison with conventional layouts. European Journal of Scientific Research, ISSN: 1450–216X/1450-202X, Volume 94 Issue 2, January 2013, pp. 242–252, EuroJournals Publishing, Inc. 2012.

Mauro, R., Guerrieri, M., 2013b. Right-turn bypass lanes at roundabouts: geometric schemes and functional analysis. Modern Applied Science, ISSN 1913–1844 (Print) ISSN 1913–1852 (Online), Canadian Center of Science and Education, Vol. 7, No. 1, (pp. 1–12). DOI: 10.5539/mas.v7n1p1.

Midenet, S., Boillot, F., Pierrellée, J.C., 2012. Signalized intersection with real-time adaptive control: on-field assessment of CO_2 and pollutant emission reduction''. Transp. Res. Part D 9 (2004), 29–47.

NCHRP Report 672, 2010. Roundabouts: An Informational Guide – Second Edition. TRB, 2010.

Pecchini, D., Mauro, R., Giuliani, F., 2014. Model of potential crash rates of rural roundabouts with geometrical features. J. Transp. Eng. 140 (11), 04014055.

Tollazzi, T., Renčelj, M., Turnšek, S., 2011a. New type of roundabout: roundabout with ''depressed'' lanes for right turning – ''flower roundabout. Promet Traffic Transp. 23 (5). http://dx.doi.org/10.7307/ptt.v23i5.153, Zagreb.

Tollazzi, T.; Renčelj, M.; Turnšek, S.; Jovanović, G., 2011b. Krožno križišče s pritisnjenimi pasovi za desno zavijanje [Tollazzi, T.; Renčelj, M.; Turnšek, S.; Jovanović, G. Roundabout with ''depressed'' lanes for right turning – ''flower roundabout''] Urad Republike Slovenije za intelektualno lastnino, SI 23266 (A), 2011–07-29 [Patent No. 23266 of the Republic of Slovenia, published 29.07.2011].

Tollazzi, T., Jovanović, G., Renčelj, M., 2013. New type of roundabout: dual one-lane roundabouts on two levels with right-hand turning bypasses – ''Target roundabout''. Promet Traffic Transp. 25 (5). http://dx.doi.org/10.7307/ptt.v25i5.1230.

Tollazzi, T., 2014. Alternative Types of Roundabouts: An Informational Guide. Springer.

Tracz, M., Chodur. J, Ostrowsk, K., 2011. Roundabouts Country report – Poland. 6th International Symposium on Highway Capacity and Quality of Service, Stockholm.

Varhelyi, A., 2002. The effect of small roundabouts on emissions and fuel consumption: a case study. Transp. Res. Part D 7 (2002), 65–71.

Wilkinson, K.E., Lundkvist, J., Netrval, J., Eriksson, M., Gulaim, A., Kessler, G., 2013. Space and time resolved monitoring of airborne particulate matter in proximity of a traffic roundabout in Sweden. Environ. Pollut. 182, 364e370.

Yu, F., Yao, L., Liao, H., 2013. Analysis of motor vehicle exhaust emissions based on COPERT model. In: Proceedings of the 4th International Conference on Transportation Engineering, pp. 529–536.

Yap, Y.H., Gibson, H.M., Waterson, B.J., 2013. An International Review of Roundabout Capacity Modelling. Transp. Rev. 33 (5), 593–616.

Yedla, S., Shrestha, R.M., Anandarajah, G., 2005. Environmentally sustainable urban transportation - Comparative analysis of local emission mitigation strategies vis-à vis GHG mitigation strategies. Transp. Policy 12 (3), 245–254.