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A model for evaluating the environmental and functional benefits of "innovative" roundabouts

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A R T I C L E I N F O

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A B S T R A C T

This study looks at the singling out of a multi-parameter criterion for choosing conventional or innovative roundabout layouts, by taking functional, environmental and economic aspects into consideration. The performances of three conventional roundabouts (with different lane number at entries and through the ring), turbo-roundabouts and roundabouts with right-turn bypass lane on all the arms (flower roundabouts) have been compared in terms of vehicle delays and pollutant (carbon dioxide, nitrogen oxides, particle pollution (PM_{10} and $PM_{2.5}$)) emissions. By means of closed-form capacity models and with the help of COPERT IV© software, several traffic simulations have been carried out, referred to yearly peak flow values Q_{max} and ranging between 1300 and 3300 veh/h, starting from a typical annual traffic demand curve in urban areas. The estimation of cumulative vehicle delays and annual pollutant emissions, together with construction and maintenance costs has allowed working out overall costs for each roundabout under consideration, depending on the traffic demand. Thus, the proposed model allows finding the most cost-effective geometric solution as to overall costs for a comprehensive case record of traffic values.

Introduction

In the last decades the recourse to roundabout intersections has been more and more common in urban and suburban areas, in such geometric layouts turn out to be safer (Mauro and Cattani, 2004) and provide many more benefits than conventional intersections, with or without traffic lights. Among these benefits, there is also a reduction in traffic pollutant emissions with relevant effects on the environment (Varhelyi, 2002). Through empirical surveys Mandavilli et al., 2008 have shown that roundabouts allow to obtain a remarkable reduction in air pollutants compared to All-Way Stop Controlled (AWSC) as well as Two-Way Stop Controlled (TWSC) intersections. The percentage reductions in pollutants have been estimated to 21–42% CO, 16–59% CO_2, 20–48% NO_x, 17–65% HC in the daytime (AM) and during the night (PM) respectively.

Pollutant emissions at intersections are usually estimated through two very distinct phases of analysis: the former is designed to evaluate capacity performances and vehicle delays; the latter aims at determining air pollutant emissions on the basis of many parameters among which traffic flows, delays, speeds and vehicle fleet types (Gokhale, 2012).

In order to estimate the capacity and measure of effectiveness (MOE), closed-form models (e.g. for conventional roundabouts Brilon et al., 1997; Brilon, 2005, 2012), or microsimulation software packages (e.g. AIMSUN, VISSIM, etc.) can be used.

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Whereas air pollutant emissions can be estimated through several models (Bhandari et al., 2013; Pérez-Martínez and Miranda, 2014), like, for example, CMEM, GREET, PHEM, VRPTW and COPERT.

In the present work, like it will be specified in the following, has been adopted a model developed by present authors for the capacity and MOE evaluation, while has been utilized the COPERT IV© model for the evaluation of the pollutant emissions thanks to its direct consideration of the actual running fleets.

Among roundabouts, particularly interesting are turbo-roundabouts (Fortuijn, 2003, 2009) and roundabouts with right-turn bypass lanes like flower roundabouts; they both have been designed in Europe quite recently (Tollazzi et al., 2010, 2011).

In European countries (e.g. Holland, Slovenia, Poland) several turbo-roundabouts have already been constructed for their undoubted potentialities in terms of traffic moderation and safety (De Luca et al., 2011). According to a recent unofficial estimation, back to the end of 2013, there were 317 operational turbo-roundabouts all over the world: 314 in Europe, 2 in the USA, 1 in Canada and 1 in South Africa.

In turbo-roundabouts the lanes of the circulating carriageway, in entry and exit arms, are physically separated each other by kerbs (Turborotondes, CROW 2008). By considering this and the lane pre-selection system before entering the roundabout, capacity and levels of service can be determined through a lane by lane analysis (Akcelik, 2005). It has been shown that the capacity of each roundabout entry is influenced not only by single lane capacities, but also by the antagonist flow, the combination of the flows along circulating lanes, users' behavior (through the psycho-technical parameters T_c, T_f and T_{min}) and by the balance of traffic flows on the arm (Corriere and Guerrieri, 2012).

Roundabouts with right-turn bypass lanes at all arms are characterized by the fact that right-turning vehicles do not go into the ring but benefit from an appropriate bypass lane. Flower roundabouts are a particular roundabout type with one circulating lane, a lane at entries and an additional lane to turn right. In flower roundabouts there are no weaving manoeuvres on the ring but there are the typical eight conflict points (i.e. 4 diversion and 4 entry points) of a conventional roundabout with a circulating lane. Moreover, for right-turn bypass lanes there should be also considered the diversion points related to the pre-selection manoeuvre of right-turn lane and the entry points onto the flow exiting from the roundabout (Corriere et al., 2013a). These conflict points (4 diversion and 4 entry points) are set at a certain distance from the roundabout, where the effect on the speed moderation is less marked. Therefore, on the one hand, there is the advantage in eliminating exchange manoeuvres (which, however, occur along the ring and with modest speeds in double-lane roundabouts), on the other the disadvantage of introducing diversion and entry manoeuvres away from the roundabout. Overall, in a flower roundabout there are 16 conflict points, that is 8 conversion and 8 entry points.

In the last few years a lot of research has been done to compare the capacity of turbo- and flower roundabouts with that of conventional roundabouts (Mauro and Branco, 2010); however, very little attention has been given to "environmental performances" on air pollutant emissions which, as a matter of fact, are a discriminating factor in choosing the most suitable intersection especially in urban contexts, where appropriate policies are required to reduce pollution from the transport system (Wilkinson et al., 2013; Midenet et al., 2004; Pérez-Martínez and Miranda, 2014).

All above considered, through appropriate closed-form algorithms for the functional analysis (capacity and delays) of conventional and innovative (turbo and flower) roundabouts, layouts and by the help of the COPERT IV© software, the study has indicated the emissions of some air pollutants (CO_2, NO_x, $PM_{2.5}$ and PM_{10}) in several traffic conditions (yearly total volume and peak hour volume), starting from a given matrix of flow distribution.

The study has thus aimed to evaluate and compare the overall costs of seven roundabout layouts: 3 conventional (one lane at entries and one at the ring – layout (1 + 1); one lane at entries and two at the ring – layout (1 + 2); two lanes at entries and two at the ring – layout (2 + 2)) and 4 innovative (turbo-roundabout, flower-roundabout with bypass lanes controlled by Stop, Yield or with an acceleration lane "Free flow slip lane"). – and to separately examine the contributions of construction costs, costs due to vehicle delays and costs attributable to air pollutant emissions over a set time period (10 years).

A suitable criterion for choosing the best geometric solution based on the annual traffic conditions and the peak hour volume has then been established.

Model for the estimation of capacity and delays in turbo-roundabouts

Several studies have shown how much safer may be turbo-roundabouts than conventional double-lane roundabouts, since they have less conflict points (14 instead of 24) and traffic lanes split before entering the ring and at exit arms. For this reasons the evaluation of capacity, delays, queues and levels of service needs a separate examination of the two entry lanes (the former used for right-hand turning, the latter for the crossing and left-hand turning) (Mauro and Branco, 2010). In case of simultaneous presence of vehicle and pedestrian flows (provided with unsignalised crossing at arms (Rouphail et al., 2005; Schroeder et al., 2008), the capacity of the two lanes and the entry can be estimated by means of the following relations (Corriere and Guerrieri, 2012; Brilon, 2005):

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