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Road Intersections Design And Environmental Performances

A new operational analysis allowed by traffic microsimulation

Tullio Giuffrè
Faculty of Engineering and Architecture
University of Enna Kore
Enna, Italy
tullio.giuffre@unikore.it

Antonino Canale
Faculty of Engineering and Architecture
University of Enna Kore
Enna, Italy
antonino.canale@unikore.it

***Abstract*—Nowadays, when designing a road intersection, it is necessary to take into account the environmental performances, which are actually considered as relevant as the traditional criteria related to safety, functionality and costs. The aim of this research is both environmental analysis and calculation of pollutant emissions for four different at-grade four-arm intersections (standard traffic-signal controlled intersection, one-lane, two-lane and turbo-roundabout), referring to different traffic flows distribution. The results of this research are summarized by three-dimensional surfaces, which can be a useful tool for the designer to predict the environmental impact that each scheme would cause and choose the most appropriate one.**

Keywords—road intersections; comparative analysis; design criteria; environmental performances; traffic microsimulation

I. INTRODUCTION

The road pollutant emissions, particularly in urban contexts, are correlated to the geometrical features of the road infrastructure and to the intensity and structure of traffic flows.

The primary aim of the research was to perform a comparative analysis among four different at-grade-four-arm intersections (a signalized intersection, an unsignalized intersection, a conventional single-lane roundabout and a turbo-roundabout) by means of the estimation and calculation of the most significative pollutant emissions. In particular, the emissions of carbon monoxide (CO), carbon dioxide (CO_2), particulate matters (PM_{10}), volatile organic compound (VOC) and nitrogen oxides (NO_x) were computed, considering different traffic flows and different traffic distribution matrices.

In order to provide to the road administrations a methodology that facilitate their choice and evaluation of the most ecologically efficient geometry, the four different intersection schemes have been analysed with microsimulation tools (specifically, the PTV VISSIM and TNO EnViVer software packages).

Then, the research background is related to the latest scientific research [1][2][3][4][5][6] in the field of road infrastructures. These have been directed to design new types of road intersections, with the vision to increase their capacity and improve their safety conditions. Among the most interesting solutions, there are schemes similar to traditional roundabouts, even if characterized by somewhat different operational modes. As for example they are turbo-roundabouts and flower roundabouts, whose individual capacity and safety peculiarities allow them to be implemented more frequently in Europe (especially in the Netherlands, Germany and East Europe) in order to redevelop the black spots of the road network or to improve the performances of the intersections already in operation.

So, overall the Europe and also elsewhere, modern roundabouts, which are functioning as one of the safest forms of intersection control [7] [8] [9] and improving traffic flow at intersections, have the additional advantage of cutting down vehicular emissions and fuel consumption by reducing the vehicle idling time intersections and thereby having a positive effect on the environment. It seems that the situation is even much better in the case of alternative types of roundabouts [1].

Several authors have recognised that the relative performance of turbo-roundabouts is largely dependent on the local traffic conditions and layout [2] [3] [4] [5].

In terms of environmental effect on intersection operations, it is possible to consider that many studies are often focused on simulation models in order to integrate simulation-generated vehicle dynamics data to microscopic emission models and quantify the effect of roundabouts on pollutant emissions.

Mandavilli et al. [10] used aaSIDRA to compare the emissions produced from stop controlled intersections with single-lane roundabouts.

Ahn et al. [11] chose to create microscopic simulation models integrated to VISSIM to compare emissions produced in a signalized intersection, a stop controlled intersection and a roundabout.

More than 60% of the analysed studies includes only road traffic modelling and emission modelling [12]. The integration of air quality modelling with traffic simulation models was done in only 30% of the studies analyzed [13] [14]. Within the analyzed studies, only nine studies link a microscopic traffic model with an air quality model. Out of these, seven studies apply average speed emission models [14][15] [16] [17] [18] [19] and two of them use instantaneous emission models [13] [20].

Giuffrè et al. [6] describe a criterion based on functional, environmental and economic aspects for comparing not conventional roundabouts with innovative one- or two-level roundabouts in urban areas.

In summary, it can be observed that the use of instantaneous emission models to link both road traffic and air quality models has not been totally well addressed among the relevant literature. Such results can be explained by the fact that to assess the environmental impacts of urban road traffic policies an additional work in the traffic modelling is required in order to produce trustworthy results.

Abou-Senna et al. [21] presented a detailed examination of traffic-related key parameters, specifically traffic volume, speed, and truck percentage, using four different vehicle activity characterization approaches. The corridor was modelled using VISSIM and MOVES 2010.

Giuffrè et al. [22] demonstrated that the emission rates are highly sensitive to stop-and-go traffic and the associated driving cycles of acceleration, deceleration, and idling.

Mahmod [23] presented a cooperative algorithm for reducing traffic emissions at signalized intersections, using the communication between vehicles and traffic signals to obtain information about the traffic signal status, testing this system in VISSIM and EnViVer.

Mathias et al. [24] implemented in VISSIM and EnViVer an environment microscopic simulation integrating the eCoMove applications without any changes from their test site implementation, to be able to influence the behavior of the vehicles according to real implementation behavior, and to systematically assess the impact of eCoMove applications.

Other researches have compared total costs [25] due to delays, pollutant emissions, construction and management costs for each design in order to identify the traffic range which makes every roundabout type more advantageous.

II. MICROSIMULATION APPROACH AND RESEARCH METHODOLOGY

Microscopic simulation models are able to represent the traffic and its evolution at any given time, taking into account the geometrical aspects of the infrastructure in detail and the real behavior of the driver, determined by the characteristics of both the vehicle and the driver.

Each traffic simulation model has its unique specific base models that include, e.g, a car-following logic, a lane-changing logic, and a gap acceptance logic.

The principles of microscopic simulation consist in calculating movements of individual vehicles based on interactions with other vehicles.

The simulations are based on mathematical models that take into account all the parameters referred to networks, vehicles and driver behavior. They are capable of analyzing and elaborating the movement of any single vehicle in the network at any given moment, based on laws that depend on the trajectory of the vehicle and of the behavior of the driver. Furthermore, they are able for each vehicle to compute useful information such as position, speed and acceleration.

For this research, VISSIM microsimulation model was used.

The precision of a traffic microsimulator is mainly associated to vehicle model, such as the methodology to define the traffic flow through the network. In contrast to less complex models that use constant speeds and deterministic car-following logic, VISSIM uses the psychophysical driver behavior model developed by Wiedemann, on the contrary to simpler models based on constant speeds and deterministic car-following logic.

To improve liability in cities and to meet stringent regulations set by the European Union, municipalities are striving to reduce the amount of greenhouse gas (GHG) and particulate matter (PM) emissions. In order to find the potential benefits of some types of intersections over others, with regard to pollutant emissions, we decided to use software tool.

Adaptive Network Signal Control (ANSC) strategies have been developed with the main goal of improving the road traffic flow in urban areas by reducing travel times and the number of stops on the strategic network. However, in addition to improving traffic flow, ANSC strategies could prove to be a useful means for reducing the GHG and PM emissions from traffic in urban areas. In order to test this hypothesis, the traffic trajectory data were collected and were analysed using the EnViVer model from TNO (Netherlands Organisation for applied scientific research), which takes into account the velocity-time profiles of individual vehicles and estimates the emitted CO_2, NO_x and PM_{10}. [26]

EnViVer is one of the most performing and widespread software of environmental data processing in road field according to CORINAIR model. Furthermore, EnViVer is totally compatible with VISSIM microsimulation software.

Then, for the purpose of the research, the microsimulation tool was used to detect some road intersection performances. Indeed, as it is well known, the available maneuvers in road intersections are driving straight, right-hand turning and left-end turning. These manoeuvres may be regulated by yield, stop and traffic lights.

For each intersection scheme, the left-hand turning is the most demanding because of the higher number of conflict points along the vehicle trajectory and because of the longer time that vehicles need to pass the intersection.

A large number of traffic simulations were run by considering three traffic distribution matrices ρ1, ρ2 and ρ3 – the O/D matrix fixed vehicle demand at each arm of the intersection - showed in Fig. 1 referring to HCM [27] theory. The total entry arm flows ranging between 1,120 and 2,480 veh/h equally distributed among the four arms of each intersection because for this research, 80% of each intersection scheme capacity was chosen as maximum value to study the pollution in a not saturated traffic condition.

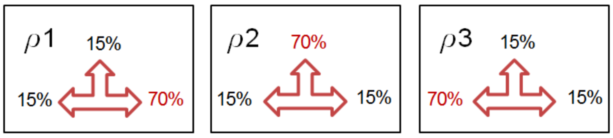

Fig. 1 *ρ1, ρ2 and ρ3 traffic distribution matrices*

The first simulations were run on a free four-arm intersection Fig. 2. Each arm of the intersection has two lanes (one for each direction). For the simulations, three matrices were used: ρ1, ρ2 and ρ3 with 1,120 veh/h. The capacity of this intersection layout is 1,400 veh/h and, for this research, a traffic volume equal to 80% of the capacity was chosen to study the pollution in a not saturated traffic condition. It is here required to yield to vehicles coming from the right.

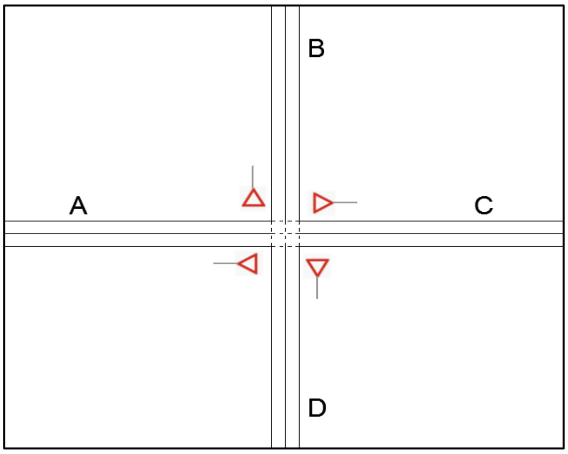

Fig. 2 *Four-arm unsignalized intersection scheme*

The simulated conventional roundabout is a four-arm one-lane roundabout with a ring of external diameter of 13 m, internal diameter of 8 m and a ring lane width of 5 m as showed in Fig. 3. Six different matrices were used for the simulations: ρ1, ρ2 and ρ3 with 1,120 veh/h and ρ1, ρ2 and ρ3 with 1,280 veh/h because the capacity of this intersection is 2,000 veh/h and, for this research, 80% of the capacity was chosen to study the pollution in a not saturated traffic condition.

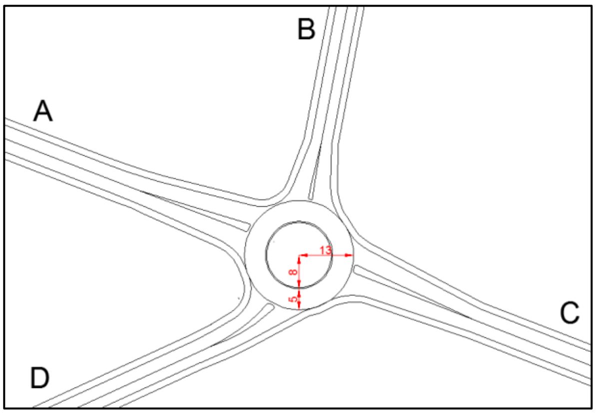

Fig. 3 *Four-arm one-lane roundabout scheme*

The third simulated intersection was a signalized four-arm intersection. Each arm of the intersection has two lanes (one for each direction) and the lane width is 3.50 m as drawn in Fig. 4. The traffic light cycle time modelled on the signal program is of 50 seconds: 20 seconds of green light, 3 seconds of yellow light and 24 seconds of red light. Several simulation was run for this intersection. Nine different matrices were used for the simulations: ρ1, ρ2 and ρ3 with 1,120 veh/h, ρ1, ρ2 and ρ3 with 1,280 veh/h and ρ1, ρ2 and ρ3 with 2,048 veh/h. The capacity of this intersection is 2,480 veh/h and, for this research, traffic volumes up to about 80% of the capacity were chosen to study the pollution in a not saturated traffic condition.

The simulated four-arm turbo-roundabout has four lanes (two for each direction) in the main direction (A-C) and two lanes (one for each direction) in the other direction.

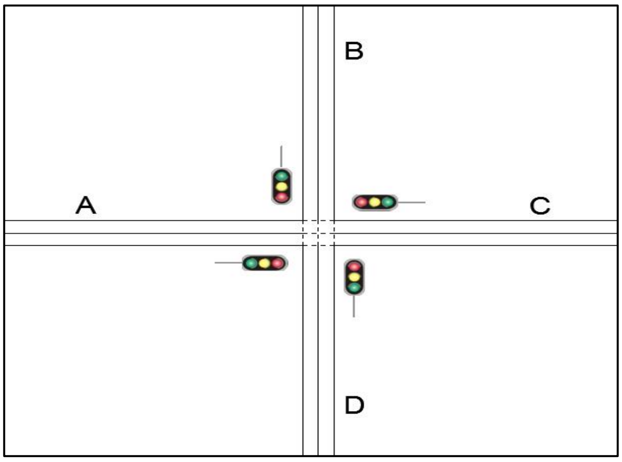

Fig 4 *Four-arm signalized intersection scheme*

The turbo-roundabout ring is not a circumference because it has not just a radius, but it has eight radii. The ring average external diameter of the ring is 28 m, the internal average diameter is 18 m and each ring lanes width is 5 m (see Fig. 5). The simulations run for turbo-roundabout were twelve with the same number of different matrices: ρ1, ρ2 and ρ3 with 1,120 veh/h, ρ1, ρ2 and ρ3 with 1,280 veh/h, ρ1, ρ2 and ρ3 with 2,048 veh/h and ρ1, ρ2 and ρ3 with 2,480 veh/h. The capacity of this intersection is 3,100 veh/h and, for this research, traffic volumes up to 80% of the capacity were chosen to study the pollution in a not saturated traffic condition.

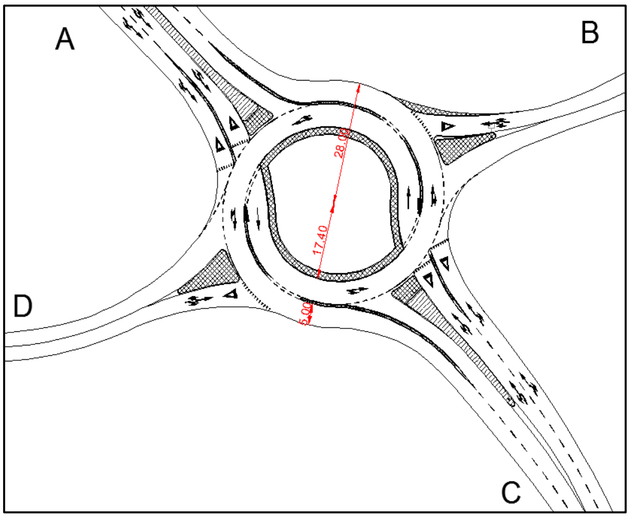

Fig. 5 *Four-arm turbo-roundabout scheme*

For each case, a wide variety of pollutants was calculated: carbon monoxide (CO), carbon dioxide (CO_2), oxides of nitrogen (NO_x), particulate matter (PM_{10}) and volatile organic compounds (VOC). The calculations were made by inserting on EnViVer tool a VISSIM FZP data file containing the following vehicle instantaneous information per second outputs: vehicle number, vehicle type number, vehicle type name, simulation time, simulation second, coordinate vehicle front, weight, power, acceleration, time in network and speed. Considering these data, the software can accurately calculate the pollutant emissions; moreover, taking into account the xyz coordinates, for each simulation EnViVer returns also a map with the concentration of each pollutant in the different zones of the intersection.

III. RESULTS

Overall findings by the recent literature [6] [28] [29] [30], show that roundabouts provide environmental benefits by reducing vehicle delays and the number and duration of stops, compared with traffic signal-controlled intersections. In the roundabouts, vehicles move slowly in queues rather than coming to a complete halt, even in case of large traffic volumes. This significantly reduces the number of acceleration and deceleration cycles and time spent idling and, consequently, air quality impact and fuel consumption. Higher percentages of left turns reduce the operability of any type of intersection, with relatively insignificant effect on a roundabout [31]. The results of the research – as they are shown by the following figures – regards the comparison of different road schemes related to the following pollution emissions:

- CO (gr);
- VOCs (gr);
- CO_2 (gr);
- NO_x (gr);
- PM_{10} (gr).

The following letters were used to represent each intersection scheme:

- “U” for the unsignalized intersection;
- “R” for the roundabout;
- “S” for the signalized intersection;
- “T” for the turbo-roundabout.

Finally, the procedure described needed of several settings of the microsimulation tool. Although the methodology illustrated up to this point has obviously took a long time, especially for the calibration, the results that will be presented in the following paragraphs will be fast and easy to consult for technicians.

A. *Results of the simulations with matrix ρ1*

This paragraph shows the results of several simulations run relative to the matrix ρ1.

In the Fig. 6/a it is possible to see that just in the signalized intersection there is a peak of CO emission, especially with 2,048 veh/h; instead, the other intersection scheme performances are comparable.

The results shown in Fig. 6/b given by the microsimulation tool EnViVer are presented as a function of traffic flow.

The results provided by EnViVer show positive results for the estimated average CO_2 emissions of all four junction types. The graph in Fig. 6/c shows the increase of NO_x concentration related to the increase of traffic flow. Regarding the PM_{10} production, Fig. 6/d shows that just in the signalized intersection there is a peak, especially with 2,048 veh/h; instead, the performances of the other intersection schemes are similar. Considering VOC concentration, it is possible to see an increase of this value with traffic flow as described by the graph in Fig. 6/e.

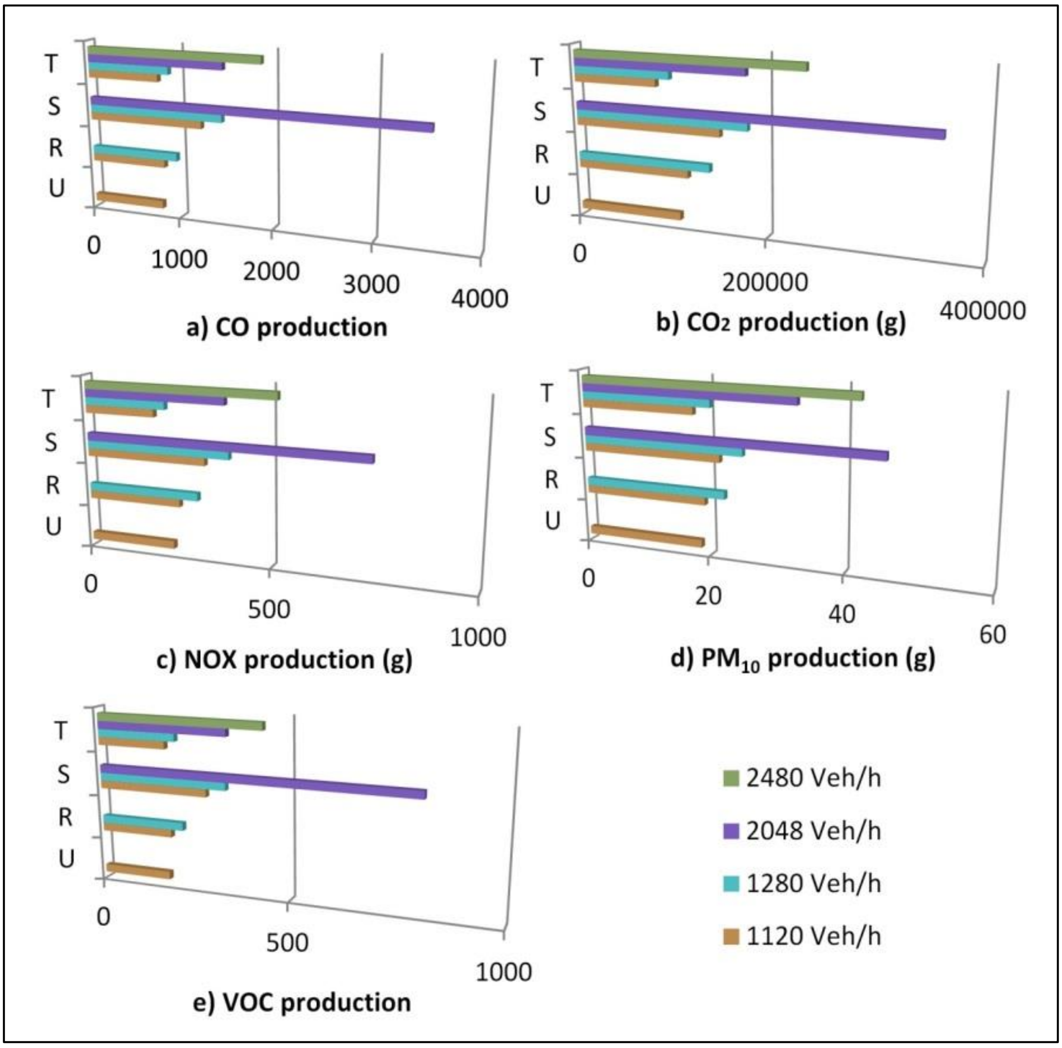

Fig. 6 *Results obtained with matrix ρ1*

B. *Results of the simulations with matrix ρ2*

A large number of simulations with VISSIM and EnViVer were also run with the matrix ρ2.

The results shown in Fig. 7/a and 7/b, given by the microsimulation tool EnViVer are presented as a function of traffic flow.

The graphs in Fig. 7/c and Fig. 7/d show the growth of the NO_x and PM_{10} concentrations related to the increase of traffic flow and it is clear that the turbo-roundabout has the best performances also in this case.

Considering the concentration of VOC, it is worth mentioning that as the value of the traffic flow increases, the peak is always found in the signalized intersection as described in the graph in Fig. 7/e.

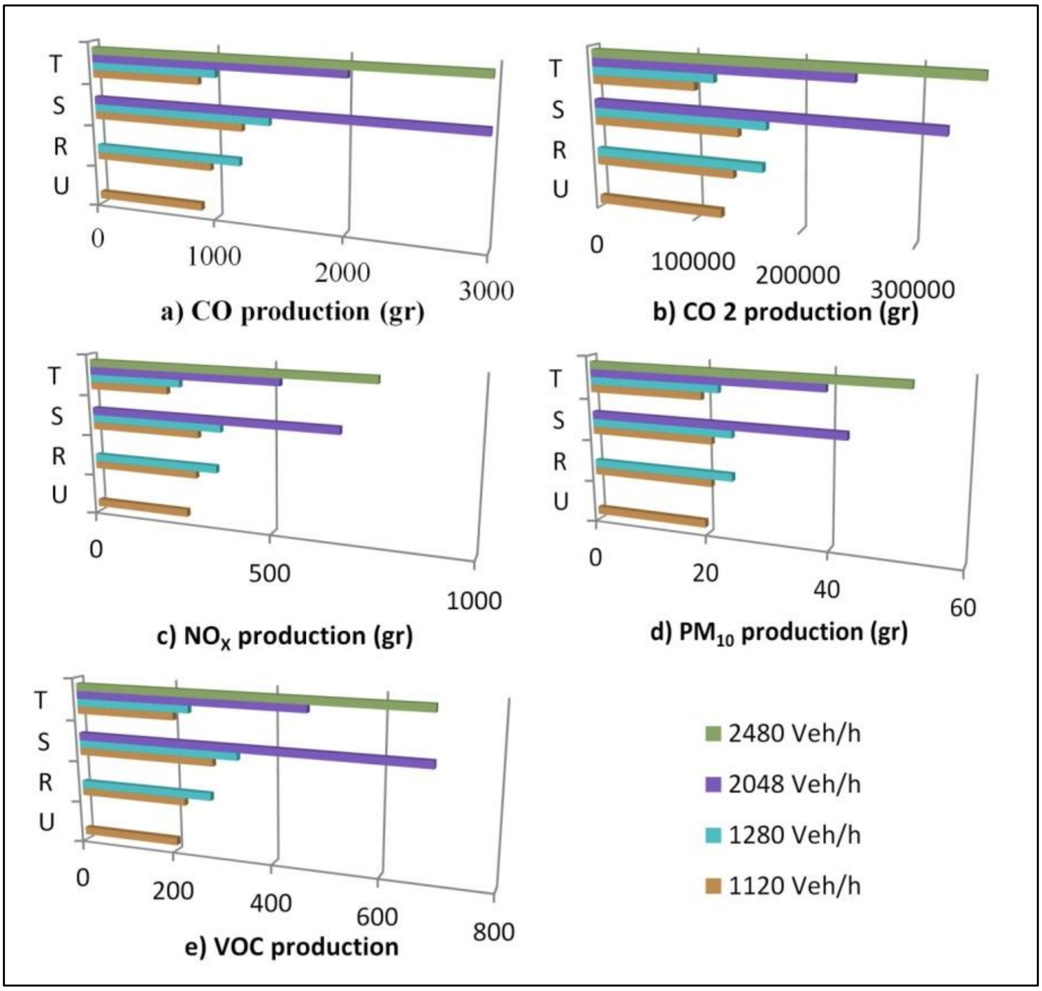

Fig. 7 *Results obtained with matrix ρ2*

C. Results of the simulations with matrix ρ3

The simulation runs using ρ3 as input matrix gave very promising results.

As for the emission of CO, shown in Fig. 8/a, the unsignalized intersection turns out to be the road scheme with the highest emissions with the 1,120 veh/h traffic volume; again, it is the signalized intersection that has the worst performances with 2,048 veh/h traffic flow.

The same results, showed in Fig. 8/b, given by the microsimulation tool EnViVer, were obtained about CO_2 emission.

The graph in Fig. 8/c shows the increase of NO_x concentration related to the increase of traffic flow.

PM_{10} emission shows in Fig. 8/d is comparable for all the intersections in the case of a traffic volume of 1,120 veh/h and 1,280 veh/h but at higher volumes the turbo-roundabout turns out to be the best performer.

The obtained VOC concentration values is shown in Fig. 8/e. It says that the unsignalized intersection has the highest VOC emission with the 1,120 veh/h traffic volume, whereas the signalized intersection has the highest emission with 2,048 veh/h traffic flow.

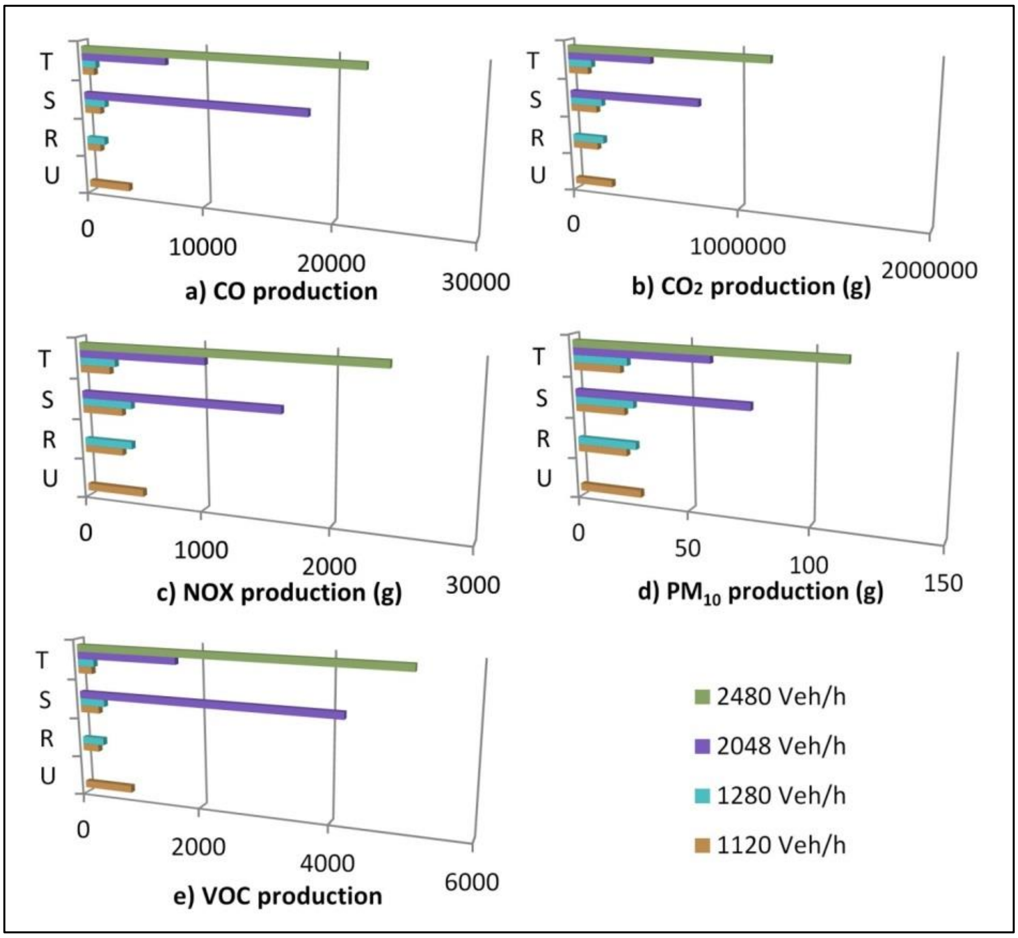

Fig. 8 *Results obtained with matrix ρ3*

IV. OUTLINES DISCUSSIONS

Thanks to the microsimulation it was possible to estimate CO and VOC emissions; finally, the results of the microsimulations run by VISSIM were then elaborated by EnViVer in order to compute CO_2, NO_x e PM_{10} emissions.

So, as main outline derived by the research it was created a three-dimensional surface for each indicator or covariate. The surface represents the rate of variation of the aforementioned data as a function of both the traffic flow and the distribution matrix of the traffic flow, where:

- Q_1 is 1,120 veh/h;
- Q_2 is 1,280 veh/h;
- Q_3 is 2,048 veh/h;
- Q_4 is 2,480 veh/h;

As for example, the Fig. 9 shows the three-dimensional environmental performance surface related to CO emission in the analyzed turbo-roundabout. Then, by considering turbo-roundabout, it is possible to see an increase of about 4 times as much relate to double value of traffic flow. The increase of CO concentrations is more evident especially when the capacity value up to 1,280 veh/h.

The three-dimensional surfaces shown above, can be a useful tool for the designer who already knows the expected traffic data, to predict the environmental impact that each scheme would cause and choose the most appropriate one.

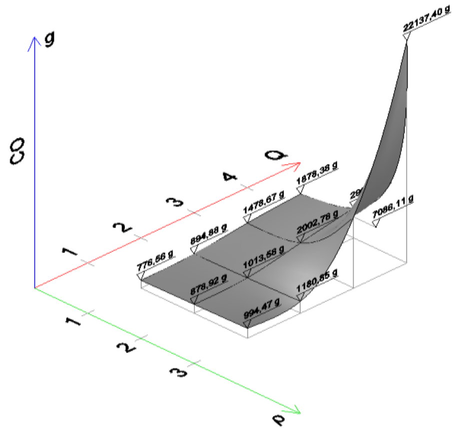

Fig. 9 *Turbo-roundabout CO production 3D surface*

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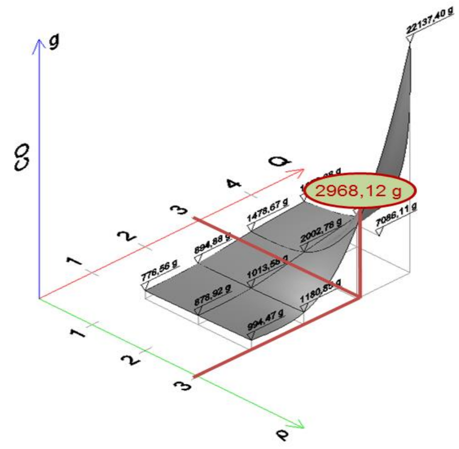

Fig. 10 *Usage* example *of the 3D surface*

For instance, for a signalized intersection with a traffic flow of about 2,048 veh/h during peak hours and a distribution matrix similar to ρ3, the designer would quickly know how the CO emission, e.g., would be in the case of a turbo-roundabout, as shown in Fig. 10, without the need of any computation or simulation. The same typology of surface was obtained for each other calculated pollutant emission, as shown in Fig. 11.

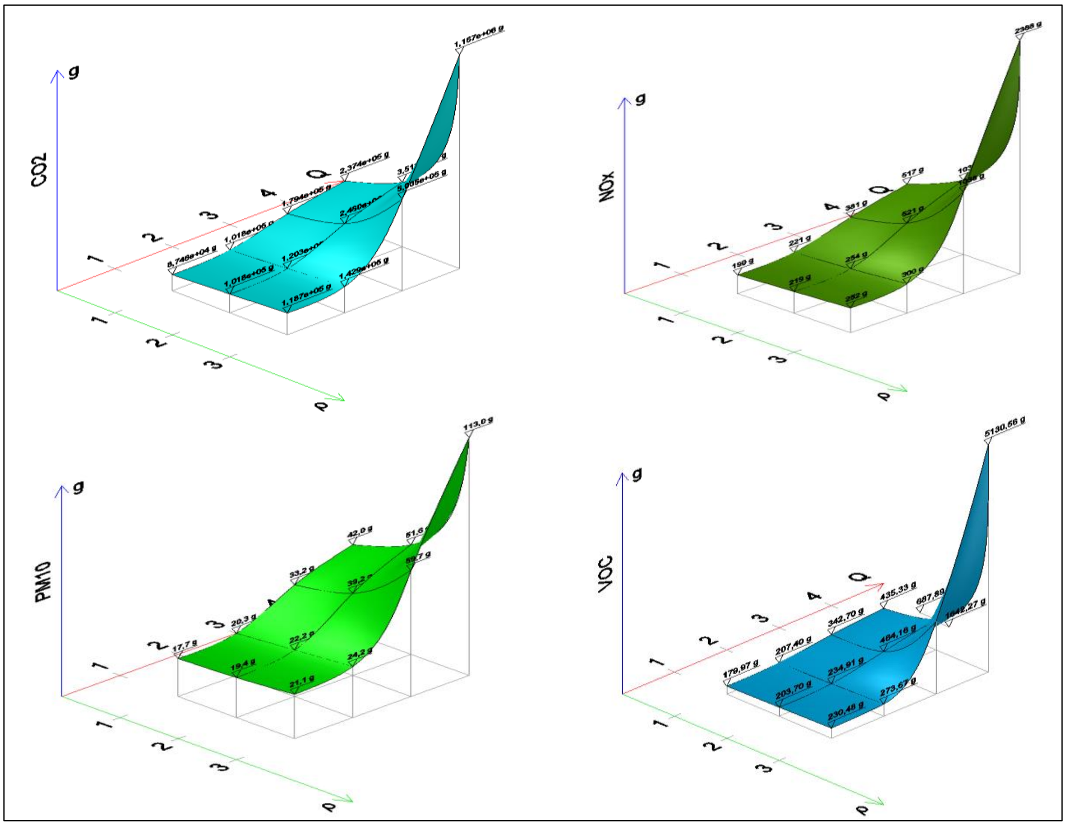

Fig. 11 *Turbo-roundabout CO_2, NO_x, PM_{10} and VOC concentration 3D surfaces*

V. CONCLUSIONS

Four different at-grade four-arm intersections layout have been analyzed with microsimulation tools, in order to be able to provide the designer with solid means that facilitate their choice and evaluation of the most ecologically efficient geometry:

- unsignalized intersection;
- single-lane conventional roundabout;
- signalized intersection;
- unconventional roundabout (turbo-roundabout).

In order to reach the research goals, for the computation of pollutant emissions of the vehicles PTV VISSIM and TNO EnViVer were used.

Three different distribution matrices were used with four different traffic flow values, up to the 80% of their capacity value.

It was created a three-dimensional surface for each covariate or pollutant emission factor. The surface represents the rate of variation of the operational and emission parameter as a function of both the traffic flow and the distribution matrix of the traffic flow.

The previous discussion on emission factors related with traffic events shows that, with high accuracy, it is possible to reach the estimate of polluting emissions made by vehicles in a determined intersection layout, from emission factors proper of each functional settings (e.g. through single mode emission factor) and from the distribution origin-destination pattern defined at microscopic level. In practical applications, modal activity derived from the methodologies explored via traffic microsimulation models could lead to road design improvement.

In conclusion, what has been discussed represents the starting point of a new and a promising way to assess the environmental performances of intersection layout, which shall lead – with further studies and improvements – to a versatile and reliable predictive tool for researchers and technicians alike in the field of road design.

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