Environmental Performance Evaluation at Urban Roundabouts

Francesco Acuto, Tullio Giuffrè, and Anna Granà

Abstract Transformation toward greener, healthier and safer management of urban mobility demand is needed soon. Smart tools are available to assess the impact of new infrastructural projects and road facilities also from an environmental point of view. In this pilot study pollutant emissions at a sample of urban roundabouts were estimated employing the Vehicle Specific Power methodology which needs second-by-second speed profiles both gathered in the field and simulated in AIMSUN. The versatility of the micro-simulation model for a calibration aimed at improving accuracy of the emissions estimates was tested in order to ensure that second-by-second trajectories experienced in the field properly reflected the simulated speed-time profiles. The results confirmed the feasibility of the smart approach that integrates the use of field-observed and simulated data to estimate emissions at urban roundabouts. It is also revealed friendly in collecting information via smartphone and in the subsequent data analysis, and provided new opportunities for a large-scale data collection through a digital community.

Keywords Roundabout · VSP methodology · Air emissions · AIMSUN

1 Introduction

The urban transport system is going great change. Current technologies to support safer and environmentally-friendly forms of personal and collective mobility, and new trends in autonomous driving call for road infrastructures suited to meet the

F. Acuto · A. Granà (✉)
Department of Engineering, University of Palermo, Palermo, Italy
e-mail: anna.grana@unipa.it

F. Acuto
e-mail: francesco.acuto@unipa.it

T. Giuffrè
University of Enna Kore, Enna, Italy
e-mail: tullio.giuffre@unikore.it

C. Ha-Minh et al., (eds.), *CIGOS 2021, Emerging Technologies and Applications for Green Infrastructure*, Lecture Notes in Civil Engineering 203,
https://doi.org/10.1007/978-981-16-7160-9_163

current challenges of the digitalization [1]. Despite the gradual transition to alternative fuel vehicles, energy-related CO_2 emissions from road transport still cause a significant environmental impact due to the high average age of the car fleet and adaptation to the new emission standards which proceeds following the physiological rate of replacement of vehicles [2]. Understanding new infrastructural projects also from an environmental point of view allows the planners, designers, decision-makers and the public to better figure out the trade-offs of a road project or to require further investigation to determine whether a conversion of a road facility into another is feasible or it is really the preferred alternative. To meet the industrial challenges of global decarbonization, as the EU government also recommends, smart mobile devices are increasingly needed to collect vehicle activity data and to monitor emissions from road vehicles in view of a mobile crowdsensing-based system [3]. Transport-related air-quality management-level activities usually employ average speed-based and instantaneous (modal) approaches to estimate emissions from traffic [4]. The average speed-based approaches use information aggregated by vehicle type as derived from driving patterns, while instantaneous models use vehicle activity parameters (as speed, acceleration, vehicle specific power [5]) to estimate emissions. However, average emission rates from different vehicles as integrated in the emission models could provide predicted emissions quite different from emissions measured for individual vehicles in the field [6, 7]. Literature also informs that few studies have been carried out to predict instantaneous emissions by microscopic traffic simulation models especially at road intersections which are the critical part of the road network; see e.g. Ref. [8]. Based on the above, a research project started to develop a methodological approach that integrates the employ of vehicle trajectory data collected in the field using a smartphone app in a test vehicle, the Vehicle Specific Power (VSP) methodology and a microscopic traffic simulation model in order to estimate emissions at urban roundabouts. This exploratory study shows how pollutant emissions were estimated using the distributions of time spent in each VSP mode from data gathered in the field and simulated in AIMSUN [9]. The primary activities at the sampled roundabouts and the results will be summarized in the following sections.

2 Materials and Methods

2.1 Data Collection

In this case study six roundabouts located in Palermo, Italy, were selected (see Fig. 1); Table 1 shows details on geometry and traffic data.

GPS trajectories were gathered using the Speedometer GPS PRO Android app in a light passenger diesel vehicle conforming to Euro IV Standard and the specifications tested to derive emissions rates for the VSP modes [10]. Vehicle activity data were collected during 7:00 to 8:30 am peak periods on weekdays in October to November

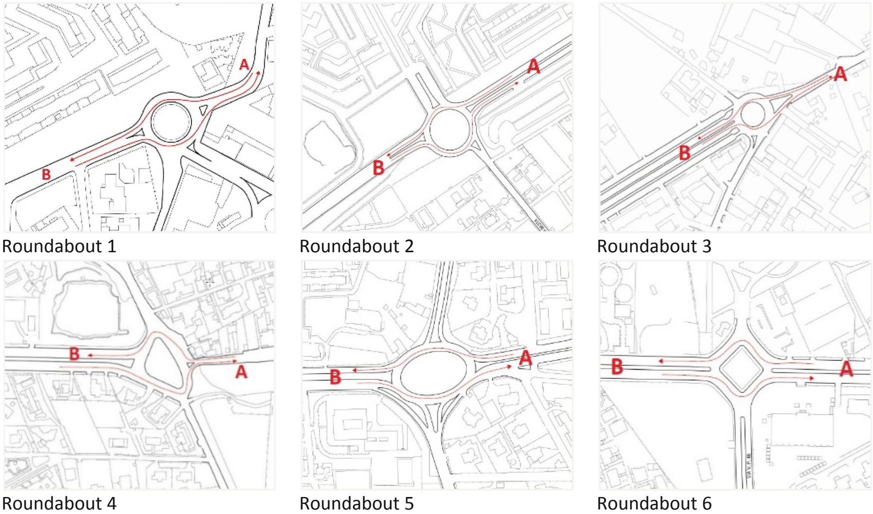

Fig. 1 The pilot sample of roundabouts within the road network of Palermo, Italy

2019; trucks did not exceed 10% in the surveyed time periods. Second-by-second speeds were extracted from the GPS trajectories of the through movements experienced by the test vehicle which entered each roundabout from the left lane (7–10 runs per site in each driving direction for a total of 94 observations); acceleration and deceleration were then computed from speed data [11]. The speed profiles with or without one complete stop were recognized [12], while those with multiple stopping on the entry approach were excluded due to their low relative occurrence.

The observations were separated by driving direction where the respective trajectories occurred in the field. Given the analogy among the curvilinear paths experienced by the test vehicle in the two driving directions (see Fig. 1), a two-tailed t-test was performed on the distributions of the observations of each relevant parameter in AB and BA directions (see Table 2). Based on the *p*-values in the table before mentioned, it cannot conclude that a significant difference exists between the two driving directions.

2.2 VSP Methodology to Estimate Emissions

The VSP expresses the instantaneous power generated by the engine to overcome the rolling resistance and aerodynamic drag, and to increase the kinetic and potential vehicle energy [5]. The simplified form of the VSP equation for a typical light passenger vehicle is based on the road grade, vehicle's speed and acceleration [10]:

$$VSP = v \cdot [1.1 \cdot a + 9.81 \cdot \sin(\arctan(grade)) + 0.132] + 0.000302 \cdot v^3 \quad (1)$$

Table 1 Information on the roundabouts of the pilot sample

No.	Entry (exit)	Outer diameter (m)	Entry (exit) lane width (m)	Ring width (m)	Mean entry (exit) speed (km/h)	Mean circulating speed (km/h)	Total entering traffic (vph)
1	3 (4)	48.00	3.50 (3.50)	7.00	22 (30)	18.00	1577
2	4 (4)	80.00	4.50 (4.50)	8.00	26 (36)	23.00	3983
3	4 (4)	50.00	3.50 (3.50)	9.00	23 (31)	20.00	2336
4	4 (4)	60.00	4.75 (4.75)	10.00	30 (42)	25.00	1317
5	4 (4)	80.00	4.00 (5.00)	9.00	25 (35)	23.00	4052
6	3 (3)	80.00	5.00 (4.50)	10.00	30 (38)	25.50	988

with *VSP* in kW/ton, the instantaneous speed v in m/s, the acceleration (or deceleration) a in m/s^2. There are 14 modes of engine regime and an emission factor by mode to estimate CO_2, CO, NO_x, and HC emissions by vehicle type [12]. To explain the proposed methodological path, in the following focus will be made on CO_2 emissions only.

For the roundabout 2 with a standard layout and roundabout 4 with an atypical layout from Figs. 1 and 2 shows the cumulative distributions of CO_2 from the second-by-second emission rates and the time spent in each VSP mode during GPS runs.

The relative increase in the percentage of CO_2 emissions with the distance from the roundabout entry is greatest in short stop-and-go events and the acceleration phase, the slope being the steepest. Repeated changes in vehicle speed in the ring provided greater CO_2 emission rates than at entries. Increase of the CO_2 emissions occurred when the test vehicle got in the ring with a minimum speed and started accelerating to reach its desired speed to exit.

2.3 AIMSUN Modeling

Based on the geometry in Fig. 1 the network models of the roundabouts were built; the urban speed limit of 50 km/h was set as the maximum speed at which each roundabout can be traveled under free flow conditions. After defining the O/D centroids and loading traffic demand data by actual O/D matrixes of the traffic counts, simulation ran under the default parameters to generate vehicle trajectories through each roundabout. AIMSUN allowed to set the vehicle attributes so that speed-time profiles of an individual vehicle quite similar to the test vehicle could be extracted from the paths between the O/D centroids. Figure 3 shows, just as an example, the observed and simulated speed-time profiles derived from the same routes traveled by the test vehicle in the fields for the roundabout 1 with a standard layout and roundabout 4 with an atypical layout from Fig. 1. The comparison between the GPS trajectories

Table 2 Two-tailed t-test for parameters distributions detected in the field

Parameter	μ_{AB}a (s.e.)	μ_{BA}a (s.e.)	t-value[b]	t-critical value $t_{0.05,92}$	t-critical value $t_{0.01,92}$	p-value (α^c = 0.05)	95% c.i. for difference in means
Max. speed (m/s)	14.46 (0.38)	14.12 (0.36)	0.65	1.986	2.630	0.516	(−0.700, 1.385)
Max. acceleration (m/s^2)	1.77 (0.07)	1.55 (0.07)	2.0	1.986	2.630	0.052	(0.004, 0.430)
Max. deceleration (m/s^2)	2.498 (0.108)	2.417 (0.11)	0.52	1.986	2.630	0.60	(−0.227, 0.390)
85th percentile acceleration (m/s^2)	0.916 (0.030)	0.868 (0.025)	1.20	1.986	2.630	0.231	(−0.031, 0.126)
95th percentile acceleration (m/s^2)	1.286 (0.039)	1.196 (0.042)	1.57	1.986	2.630	0.121	(−0.024, 0.205)
85th percentile deceleration (m/s^2)	1.420 (0.081)	1.25 (0.059)	1.68	1.986	2.630	0.100	(−0.021, 0.378)
95th percentile deceleration (m/s^2)	2.053 (0.089)	1.88 (0.085)	1.39	1.986	2.630	0.20	(−0.073, 0.417)

[a]μ_{AB} and μ_{BA} stand for the mean values of the samples of the observations of each parameter in the two driving directions (AB and BA); [b]t-value is the result of the two tailed t-test done to compare the equality of the μ_{AB} and μ_{BA} of samples of two populations with equal sample size; α^c is the significance level

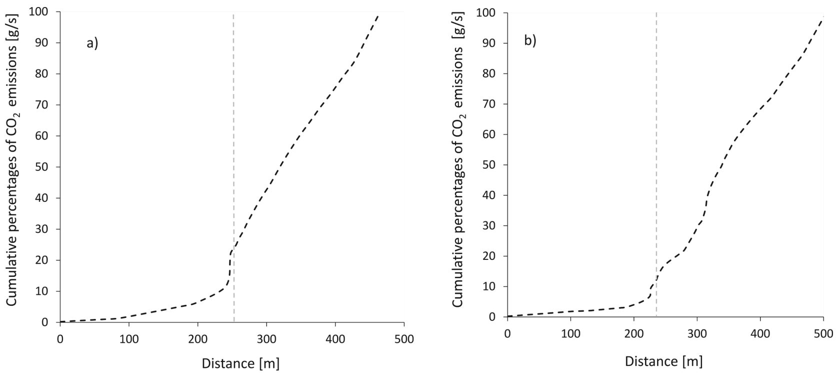

Fig. 2 Spatial distribution of CO_2 emissions based on speed profiles with one stop for roundabout 2 (A–B movement) and roundabout 4 (A–B movement) considering an influence area of 250 m

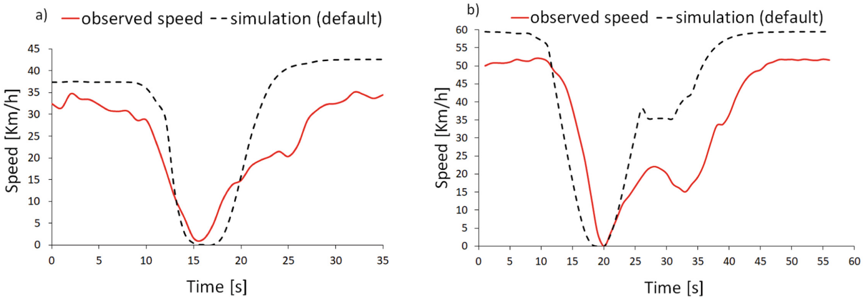

Fig. 3 Observed speed-time profiles vs (default) simulated speed profiles at: **a** roundabout 1 (movement A–B); **b** roundabout 4 (movement A–B)

collected in the field and speed-time profiles derived from AIMSUN called for model calibration.

According to Ref. [8] where AIMSUN was calibrated using analogous field-data to estimate emissions for urban arterials, two vehicle attributes of AIMSUN were selected: the Maximum Acceleration, having a default value of 3 m/s^2, and Normal Deceleration, having a default value of 4 m/s^2 [12]. As an exploratory assessment of the versatility of the micro-simulation model to explain emissions, each roundabout network model was calibrated using the mean values of the 95th percentiles of the accelerations and decelerations extracted from all the field-observed trajectories regardless of driving direction (see Table 2). Based on Ref. [8], the distribution of time spent in VSP modes under parameters calibrated with the mean values of the 95th percentiles of the acceleration and deceleration met the VSP distributions from empirical data more closely than the distribution under default parameters. Based on previous results of AIMSUN calibration process for roundabouts in Palermo, Italy [13, 14], the set of the calibration parameters above was also combined with AIMSUN parameters having influence on gap-acceptance behavior. For single-lane entry approaches a value of the driver reaction time of 0.86 s instead of the default value of 0.80 s, the minimum gap of 1.58 s instead of the default value of 0.0 s and speed acceptance of 1.0 instead of 1.1 were considered [13]. Then, for multi-lane entry approaches a value of the driver reaction time of 0.95 s instead of the default value of 0.80 s, the minimum gap of 1.33 s instead of the default value of 0.0 s and speed acceptance of 1.0 instead of 1.1 were used [14]. By way of example, for the roundabout 2 Fig. 4a shows that the distribution of time spent in VSP modes under parameters calibrated with the mean values of the 95th percentiles of the acceleration and deceleration matched the VSP distribution from empirical data more closely than the distribution under default parameters. Under the default parameters, the simulated vehicle appears to spend a high proportion of time in VSP mode 4; the proportion of time sensibly appears to reduce from VSP mode 5 onward, but it still appears in VSP modes 11–12 denoting high acceleration events. Under the parameters calibrated with the mean values of 95th percentiles of acceleration and deceleration, the time percentages were more realistic in the VSP modes 1–2 (deceleration), mode 3 (idle)

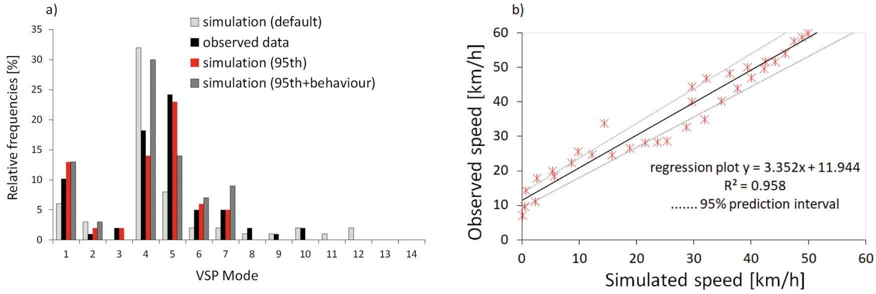

Fig. 4 Roundabout 2, movement A–B (in Fig. 1): **a** relative frequencies of time spent in VSP modes; **b** regression line of observed versus simulated speeds

and 4–7 (acceleration and cruising). Figure 4b shows for the roundabout 2 from Fig. 1 the regression line made to compare observed and simulated speeds under calibration with the mean values of the 95th percentiles of the relevant parameters.

Given that the series of the instantaneous VSP measurements and simulated values were detected at regular time points, they were interpreted as time series and used to assess how close the calibrated and the observed values were. This allowed to capture the jointed effect of speed and acceleration since the VSP is sensitive to their product. The GEH index [15] resulted smaller than 5 in more than 90% of the cases when the VSP series under calibrated parameters were compared with the corresponding empirical VSP series. Encouraging results under calibrated model parameters were also obtained in terms of GEH index when the simulated VSP series in the opposite driving directions at each roundabout were compared between them for validation purposes. Figure 5 shows the comparison of CO_2 emissions detected in the field and simulated in AIMSUN at each sampled roundabout. One can observe that the accuracy tends to be improved under calibration with the 95th

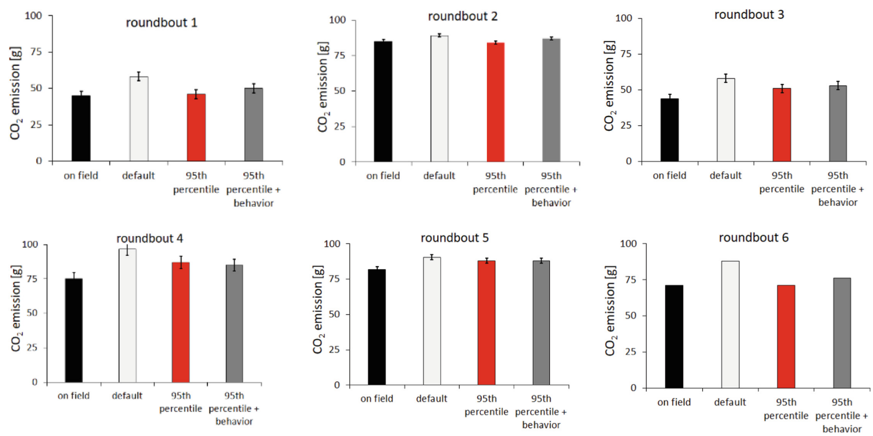

Fig. 5 Observed vs simulated CO_2 emissions at each sampled roundabout (through movements)

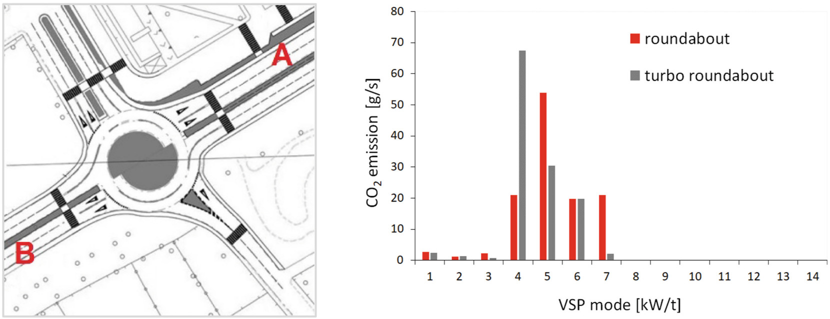

Fig. 6 Roundabout versus turbo roundabout simulated CO_2 emissions (through movements)

percentiles of the relevant parameters only. The contribution of AIMSUN behavioral parameters leans towards improved results only for roundabouts with atypical design due to the constraints of the surrounding built environment. At last, Fig. 6 shows the conversion of the roundabout 2 into a turbo design of equal size and the CO_2 emissions by VSP mode; see also Ref. [12]. Despite comparable emission amounts, one can observe a higher time spent in acceleration (mode 4) for the turbo roundabout than the traditional roundabout as typical operational standard the for turbo roundabout settlement.

3 Conclusions

The paper describes the methodological approach for estimating pollutant emissions at urban roundabouts that integrates second-by-second vehicle trajectory data collected in the field by a smartphone app, the Vehicle-Specific Power (VSP) methodology and a microscopic traffic simulation model. The research is referred to a case study of six roundabouts installed in the road network of Palermo, Italy, where pre-existing conditions of the built environment may have constrained the entry and exit geometry, or approach alignment, and consequently driving behavior through the roundabouts. The comparison between individual GPS trajectories collected in the field and second-by-second speed profiles derived from AIMSUN called for model calibration. The results of the exploratory analysis highlighted that calibrating the model parameters produced realistic VSP distributions and resulted effective in improving emissions estimates. They also gave insights on the use of simulation data in the air emission impact assessment of new planning alternatives or conversion of a road entity into another layout operation. Thus, the main finding is referred to the positive potential of a novel attitude in the conceptualization and performance evaluation of roads, in order to push forward urban infrastructural projects with the worldwide shared long-term ambitions for a low-emission mobility.

References

1. Deluka Tibljaš, A., Giuffrè, T., Surdonja, S., Trubia, S.: Introduction of automated vehicles. Roundabouts design and safety performance evaluation. Sustainability 10:1060, (2018).
2. National Research Council. Transitions to Alternative Vehicles and Fuels. Washington, DC: The National Academies Press (2013). https://doi.org/10.17226/18264
3. Zhu, X.; Hu, X.; Chiu, Y.C. Design of driving behavior pattern measurements using smartphone global positioning system data. International Journal of Transportation Science and Technology 2(4), 269–288 (2013).
4. Baškovič, K., Knez M.: A review of vehicular emission models. The International Conference on Logistics & Sustainable Transport 2013. 13–15 June 2013, Celje, Slovenia (2013).
5. Jiménez-Palacios, J.L. Understanding and Quantifying Motor Vehicle Emissions with Vehicle Specific Power and TILDAS Remote Sensing. Ph.D. Thesis, Massachusetts Institute of Technology, Department of Mechanical Engineering (1999).
6. Zhai, Z., Tu, R., Xu, J., Wang, A., Hatzopoulou, M.: Capturing the Variability in Instantaneous Vehicle Emissions Based on Field Test Data. Atmosphere 11(7), 765 (2020).
7. Abo-Qudais, S., Qdais, H.A. Performance evaluation of vehicles emissions prediction models. Clean Technol. Environ. Policy 7(4), 279–284 (2005).
8. Anya, A.R., Rouphail, N., Frey, H. C., Schroeder, B.J.: Application of AIMSUN Microsimulation Model to Estimate Emissions on Signalized Arterial Corridors. Transportation Research Record Journal of the Transportation Research Board 2428(2428), 75–86 (2014).
9. AIMSUN Dynamic Simulator User Manual 8, Transport Simulation System (TSS) (2011).
10. Coelho, M. C., Frey, C. H., Rouphail, N. M., Haibo Zhai, Pelkmans, L.: Assessing methods for comparing emissions from gasoline and diesel light-duty vehicles based on microscale measurements. Transportation Research Part D 14,91–99 (2009)
11. Bokare, P.S., Maurya, A.K.: Acceleration-Deceleration Behaviour of Various Vehicle Types. Transportation Research Procedia 25, 4733–4749 (2017).
12. Fernandes, P., Pereira, S. R., Bandeira, J. M., Vasconcelos, L., Bastos Silva, A., Coelho, M.C.: Driving around turbo-roundabouts vs. conventional roundabouts: Are there advantages regarding pollutant emissions? International Journal of Sustainable Transportation, 10(9), 847–860 (2016).
13. Giuffrè, O., Granà, A., Tumminello, M.L., Sferlazza, A.: Estimation of passenger car equivalents for single-lane roundabouts using a microsimulation-based procedure, Expert Syst. Appl. 79 333–347 (2017).
14. Giuffrè, O., Granà, A., Tumminello, M.L., Sferlazza, A.: Capacity-based calculation of passenger car equivalents using traffic simulation at double-lane roundabouts. Simulation Modelling Practice and Theory 81, 11–30 (2018).
15. Barceló J.: Fundamentals of Traffic Simulation, Springer: London (2010).