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ORIGINAL ARTICLE

The Impact of Exhaust Emission from Combustion Engines on the Environment: Modelling of Vehicle Movement at Roundabouts

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ABSTRACT – Due to the increased emission of harmful exhaust components, in particular CO_2 (carbon dioxide), CO (carbon monoxide), THC (total hydrocarbons), by motor vehicles, especially in the centres of urban agglomerations, it is necessary to create traffic simulation models that allow to estimate the emissions from road transport. One of the places where the largest accumulation of vehicles in cities occurs are intersections. This contributes to increasing the number of stops and repetitions of the acceleration and braking cycle, which has a direct impact on vehicle emissions. At the same time, roundabouts are intersections with specific traffic movement characteristics, therefore it is necessary to calibrate the simulation model beforehand. The aim of the study was to develop a methodology for modeling vehicle traffic at the roundabout and compare the combustion engines emissions resulting from vehicle movement on the example of the selected roundabout case studies. Vehicle traffic modeling was performed in the Vissim traffic microsimulation program based on real data. The comparison concerned the emissions for a two-lane and a turbo roundabout for the assumed traffic volume scenarios for properly calibrated simulation models. The results show that the performance of the simulation allows for the analysis of emissions and determination of its size for each of the roundabout inlets. It is also possible to determine the general dependencies e.g. the length of the queue of vehicles in relation to the emission of the analysed exhaust components. The analysis can be used as an introduction to changes in the guides for designing road intersections concerning vehicle emissions.

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NOMENCLATURE

CO_2	carbon dioxide
CO	carbon monoxide
GEH	Geoffrey E. Harvers
GPS	global positioning system
NOx	nitrogen oxides
PEMS	portable emission measurement system
PM	particulate matter
THC	total hydrocarbons

INTRODUCTION

The variety of driving styles and characteristics of roadways in cities causes various emissions from vehicles. Fuel consumption, as well as exhaust emissions for different components of pollutants, among others CO_2, CO, NOx (nitrogen oxides), THC, PM (particulate matter), is very diverse [1-12] and depends mainly on the speed, acceleration, gradient of the road and thermal condition of the vehicle's engine. One of the points where occur the biggest accumulation of vehicle traffic in cities is intersections. In recent years, a sudden increase in the construction of roundabouts has been observed [13, 14]. The advantage of using this type of road solution is increased road safety compared to any other type of intersection [15]. The traffic characteristic of the vehicle crossing the roundabout is specific, as the geometry forces drivers to accelerate when entering and exiting. In order to determine the emissions for different roundabout solutions under real traffic conditions, it is necessary to use vehicle traffic simulation models as well as emission models. It would be very difficult to equip each vehicle crossing the roundabout with a specialised, onboard portable emission measurement system (PEMS). Therefore, to perform the emissions calculations, the micro-simulation model must be accurately calibrated [16].

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In the literature presented so far, few publications on exhaust emissions from vehicles on various solutions of roundabouts can be found [17-19]. Articles on parameters such as capacity, driving safety and roundabout delays appear more frequently [20-28]. This paper describes the comprehensive modelling of vehicle movement crossing the roundabout for the assumed simulation scenarios. In particular, the article presents the methodology of calibrating micro-simulation models of roundabouts, taking into account the vehicle driving parameters. The calibration was performed based on real data and can be used for further development work for researchers related to vehicle and emission traffic modelling. The article also presents the results of the analysis of the emission of harmful exhaust components for selected simulation scenarios for a two-lane and turbo roundabout, during peak hours and with less traffic on the road. Moreover, the relationship between vehicle emissions and the length of queues as well as mass emissions for the entire roundabout passage is also shown. The analyses presented in the paper are the first ones based on a specialised emission model for roundabouts. Therefore, the results are presented, as well as the future work that could be used to develop new guidelines for the design of roundabouts, taking into account environmental aspects.

RESEARCH METHODOLOGY

Calibration of the Roundabout Microscopic Model Concerning Emission

According to [29], the main sources of uncertainty in modelling are:

i. input uncertainty: concerns external driving factors and system data entered into the model, such as predicted speeds and accelerations,
ii. model structure errors: conceptual uncertainty resulting from incomplete understanding and simplification of descriptions of modelled processes in comparison to the observed data,
iii. uncertainty of parameters: inaccurate calibration of the parameter leads to deterioration of the output data of the model.

Therefore, calibration and verification of simulation models, especially in the aspect of their further use for the assessment of exhaust emissions from vehicles should be focused mainly on the development of detailed driving patterns. To obtain the correct emission results from simulations, the vehicle trajectory characteristics from the model should be similar to the real ones. Although certain macroscopic motion characteristics, such as travel time, queues length, give adequate results, it is not guaranteed that more complex characteristics such as acceleration profiles and vehicle speeds are sufficient for realistic prediction of exhaust emissions.

Microscopic models are often calibrated by comparing measured and simulated vehicle travel times, delays, distribution of travel time or intensity of saturation [30-34]. However, different driving trajectories can lead to the same travel times, and different driver behaviours can cause the same intensity of saturation, delays and queues. Generally, the parameter settings that give the best fit simulation results with real observations are not unique. Exhaust emissions depend on the detailed behaviour of vehicles, such as speed, acceleration, deceleration and others [35, 36]. The diagram of the work algorithm for the simulation model for calculating pollutant emission from vehicles is shown in Figure 1.

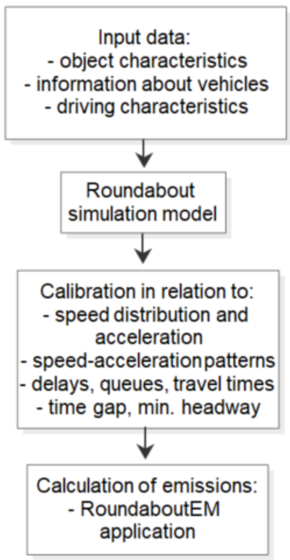


Figure 1. Calibration scheme of the roundabout model for exhaust emissions calculation.

Data Collection

Data was collected for trips through a functioning two-lane roundabout whose general technical parameters are presented in Table 1. The satellite photo of the roundabout is shown in Figure 2. Roundabout emissions and traffic characteristics data were obtained from 12 different motor vehicles, driven by nine drivers. The measurement of the location, speed and acceleration of vehicles approaching and passing through the roundabout, was made based on GPS (Global Positioning System) data. An example graph of the elevation when passing in the South-North relation through the roundabout is shown in Figure 3. Figure 3 shows the road altitude of entering, circulatory roadway and exiting of the roundabout. The altitude profile of the terrain was applied to the simulation model.

Table 1. Selected geometric parameters of the researched roundabout

Parameter	Value
The outer diameter (m)	84
The diameter of the central island (m)	69
Line width (m)	4.4
Number of inlets/outlets	4

Figure 2. A satellite photo of the researched roundabout.

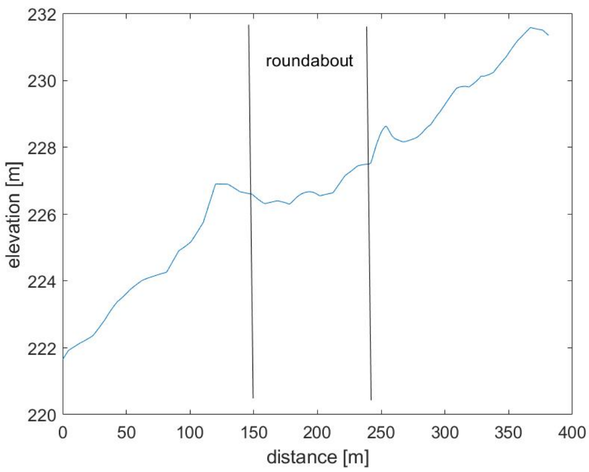


Figure 3. An example of the elevation profile for a roundabout route (South-North relation).

Calibration Process

In contrast to the modelling of the four-way intersection with the stop sign or traffic lights, the roundabouts are based mainly on the drivers' ability to accept or reject vehicle entry gaps. At intersections with traffic lights, the right of entry regulates the signal from the traffic lights, while on the roundabouts, vehicles approaching the inlet, give way only to vehicles that are currently at the roundabout. Simulation of this type of driving behaviour requires the ability to control the parameters of the critical gap and the spaces between vehicles [37, 38]. The VISSIM software controls these parameters and is suitable for modelling the movement characteristics of vehicles at roundabouts.

The simulated driving trajectories from the VISSIM must be consistent with those observed in reality. A study [38] shows that the standard values of the simulation parameters do not always reflect the actual driving trajectories. Therefore, it is necessary to carry out the calibration. Calibration of the trajectory differs from the standard calibration of parameters, e.g. delays, queues and travel time. In VISSIM calibration parameters of speed and acceleration are called desired speed and acceleration, and according to the methodology presented in work [40], the calibration process was performed.

An important issue was to select a set of such parameters that have a significant impact on the simulation results. The purpose of the calibration was the parameters described above, which are mainly responsible for the driving characteristics, and consequently, the emission namely speed and acceleration. It is also the key to obtain near-real traffic volumes, therefore, after calibrating the speed and acceleration, the parameters related to the give way, such as time gap and minimum headway were calibrated as well [41]. The Geoffray E. Harvers (*GEH*) index [42], was also checked for all traffic volumes of inlets and outlets from the researched model. The VISSIM program can be used to calibrate many parameters, but most of them have little effect on saturation, speed, acceleration and travel time. The most important parameters that have been selected based on previous work [40] are the desired speed distribution, the desired acceleration and deceleration functions, time headway (CC1), following variation (CC2), threshold for entering the state 'following' (CC3), oscillation acceleration (CC7), acceleration from standstill (CC8), time gap and minimum headway (yield sign). Parameters related to yield sign were calibrated according to real data obtained from cameras belonging to the public road administration located at the intersection as a mean value [43]. The calibration results for these parameters are presented in Table 2.

Table 2. Results of calibration of the roundabout model parameters.

Parameter	CC1	CC2	CC3	CC7	CC8	Min. gap time (right lane)	Min. gap time (left lane)	Min. headway (right lane)	Min. headway (left lane)
Standard value	0.9	4	-8	0.25	3.5	3	3	10	10
Calibrated value	1.3	5	-8	0.38	2.1	2.7	2.6	5.1	5.5

Graphs of the average values for empirical data and data after the described calibration processes are presented in Figure 4. On their basis, it can be seen that the simulation data was similar to the data from a real road test. After the calibration step, the result of the G test [44] was 0.00612 km/h for the speed distribution and 0.0589 m/s^2 for the acceleration distribution, which indicates a good representation of real data.

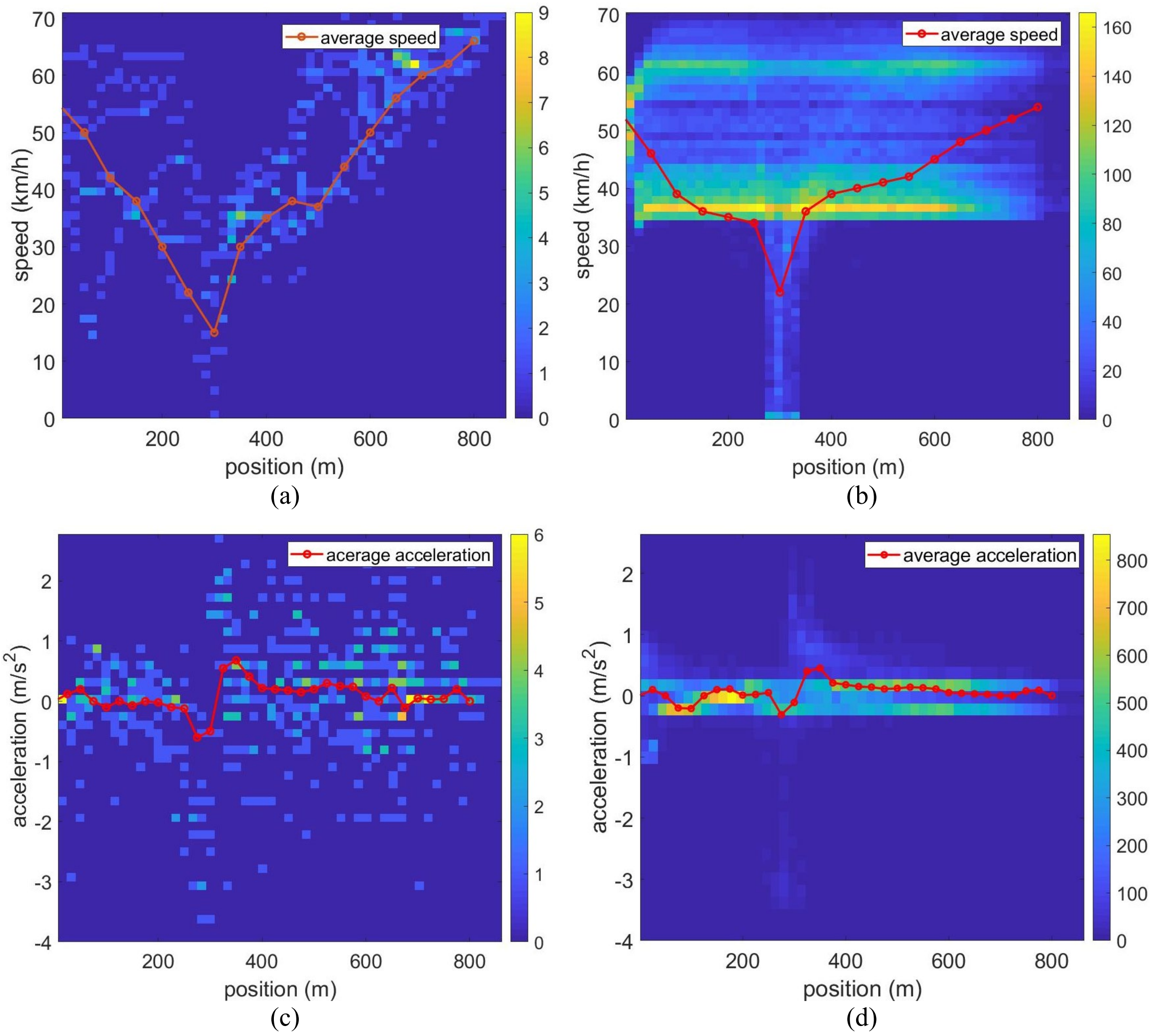


Figure 4. Observed speed and acceleration profiles for (a) recorded real speed values, (b) simulated after calibration speed values, (c) recorded real acceleration values, and (d) simulated after calibration acceleration values.

The evaluation of the calibration results was carried out based on the *GEH* statistical test, which is commonly used for this type of simulation models [45]. The purpose of the test is to compare the real traffic volume with the simulated one. If the result of the *GEH* coefficient is less than 5, the simulation can be considered as reliable. However, if the coefficient is in the range from 5 to 10, additional model calibrations should be applied. Above the value of 10, it is stated that there is a problem with the model or data [46]. *GEH* value was calculated based on Eq. (1). Examples of *GEH* values for the modelled roundabout are presented in Figure 5.

$$GEH = \sqrt{\frac{2(M-C)^2}{M+C}} \tag{1}$$

where M is the modelled traffic intensity volume, and C is the real traffic volume.

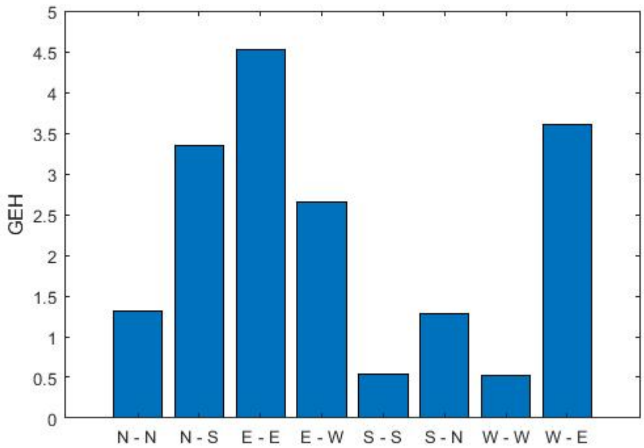


Figure 5. Exemplary values of the *GEH* coefficient for the roundabout model from the VISSIM program (for example, the N-N designation means the entry/inlet route from the north, while the N-S the northern outlet route)

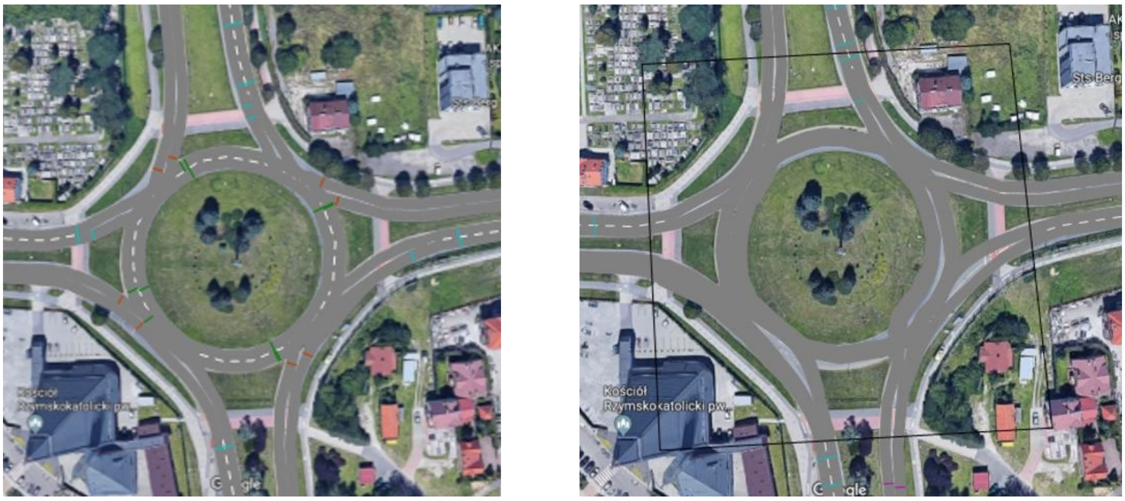
RESULTS AND DISCUSSION

Emission Maps based on the Calibrated Roundabout Model

With the help of the developed roundabout models and the RoundaboutEM [47] exhaust emission calculation model, it is possible to accurately estimate the places of harmful exhaust components emission for the analysed area. The RoundaboutEM emission model was prepared based on data from the PEMS system obtained during driving at roundabouts and allows accurate calculation of harmful exhaust components emissions for this kind of facility. The model was created using the regression method – boosted tree. It is practically impossible to measure emissions from all vehicles passing through the researched roundabout because the limitation is the installation of the PEMS system for all vehicles. Therefore, simulation models are helpful. Based on properly calibrated roundabout simulation models and using the RoundaboutEM emission model, it is possible to identify locations of high emissions of harmful exhaust components, which may allow, e.g. better location of pedestrian crossings. The prepared roundabout simulation models can also be used to compare and plan the construction (modification) of roundabouts in terms of vehicle emissions. To compare emissions that currently are on a functioning two-lane roundabout and the turbo roundabout version, a turbo roundabout model was prepared. Based on the actual traffic volume and traffic distribution at the real roundabout, it was possible to estimate emissions for these roundabout solutions. The model calibration that was carried out for the current roundabout can also be used to modify this roundabout, with the assumed traffic volume values. This is possible by applying the driving characteristics of the leader. In the case of low traffic, most of the vehicles are leaders for themselves, while in congestion conditions, a certain group of vehicles queued at the roundabout, and only those vehicles that enter the roundabout take the leader role.

The currently operating two-lane roundabout (as in Figure 2) was modelled, calibrated and compared to its alternative turbo version, as described earlier to assess the impact of such modification on the harmful exhaust components emissions. Simulation models of described roundabouts are presented in Figure 6. The assumed simulation scenarios are presented in Table 3. Scenarios A1 and A2 represent the current traffic situation for a two-lane roundabout, while scenarios A3 and A4 are their alternative counterparts for the turbo roundabout option.

Traffic data were collected for working days from induction loops located near the intersection in May 2019. Two times of the day were chosen for a detailed analysis of traffic on the roundabout and generation of exhaust emissions. The first analysed period was from 7:00 am to 8:00 am and was characterised by peak hours on the road. The second period was from 8:00 pm to 9:00 pm and was characterised by low vehicle traffic volume. The duration of the vehicle traffic simulation in the VISSIM program has been set to 4500 seconds because the model is filled for the first 900 seconds, and the values recorded during this time were not saved. Simulation is starting with zero number of vehicles, so at the beginning, a certain phase of filling the road network is needed. If this 'fill' phase of the model is not carried out, the authentic road data would not coincide with the data obtained during the simulation [48]. The models assume one class of vehicles – passenger cars because they constitute the vast majority of all vehicles that move at the researched roundabout. For the calculation of exhaust emissions, regarding the type of fuel used and the age structure of vehicles, data based on the Polish Local Data Bank was adopted [49]. According to them, the following values have been set in the model: 56% of vehicles are fueled with gasoline, 31% with diesel and 13% with LPG.



(a) two-lane roundabout (b) turbo roundabout

Figure 6. Created models from the VISSIM software.

Table 3. Tested simulation scenarios; traffic data for individual inlets to the roundabout.

Scenario	Hour	Inlet	Traffic volume (vehicle/hour)
A1	7:00-8:00 am	East	1414
		South	1103
		West	932
		North	1448
A2	08:00-09:00 pm	East	500
		South	761
		West	369
		North	852
A3		data as for scenario A1 (turbo roundabout option)	
A4		data as for scenario A2 (turbo roundabout option)	

The data for determining time-speed profiles of each vehicle, necessary for calculating exhaust emissions was obtained from the VISSIM program with a frequency of 1 Hz. An example of the speed and acceleration profile of a selected vehicle passing through a roundabout model is shown in Figure 7. The data presented in the graphs are examples of the free passage of a vehicle in the South-North relation through the inlet, roundabout and outlet. The results of the emission simulation are presented in Figure 8 and Figure 9.

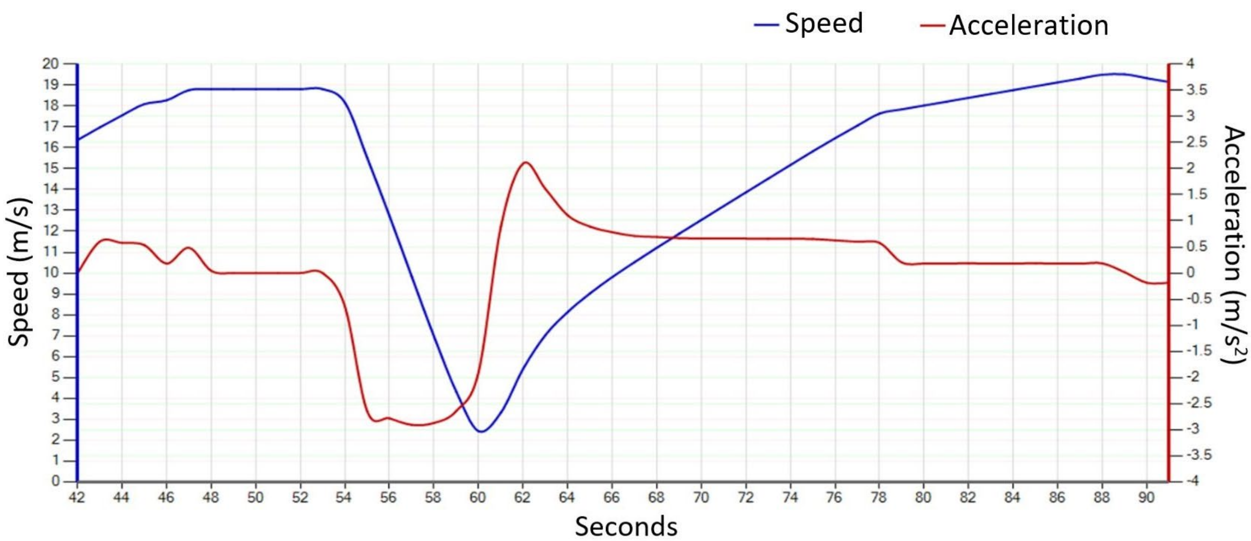
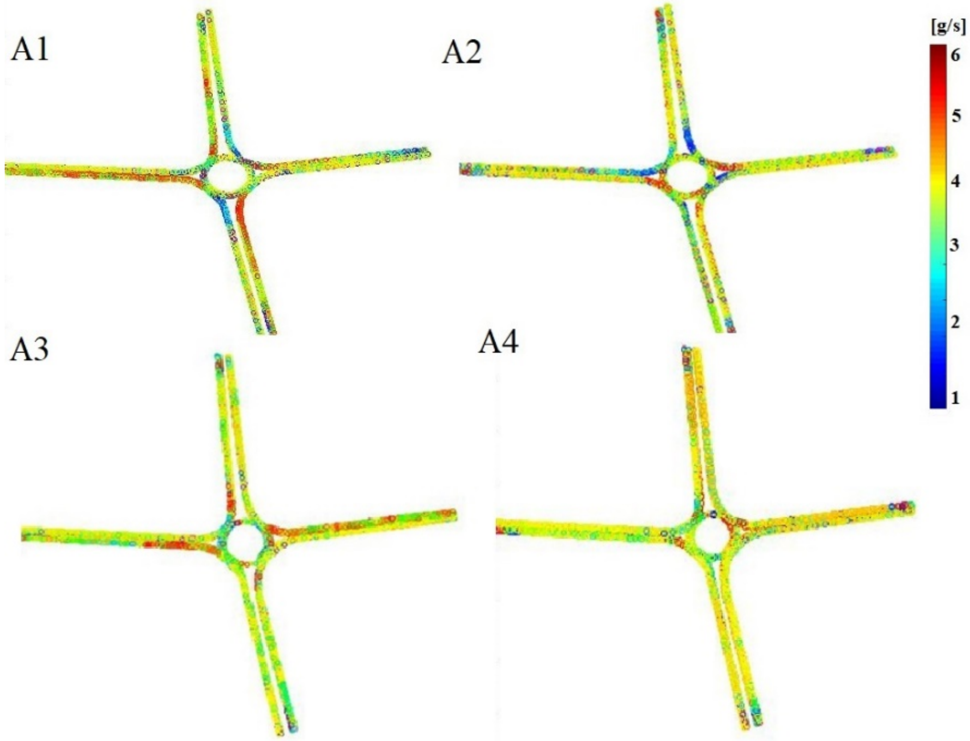
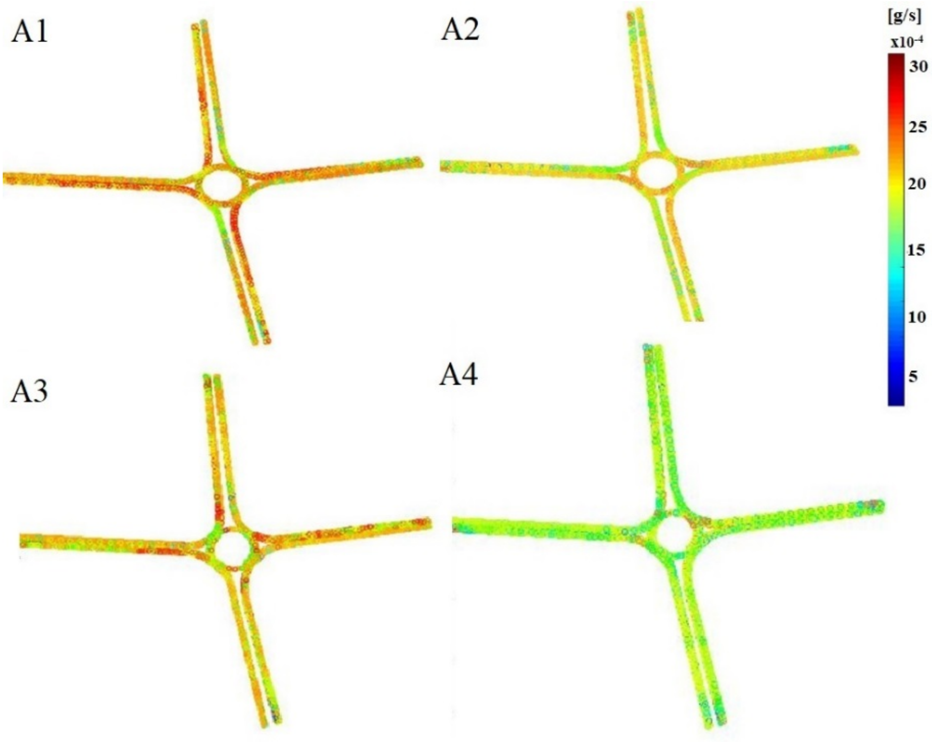


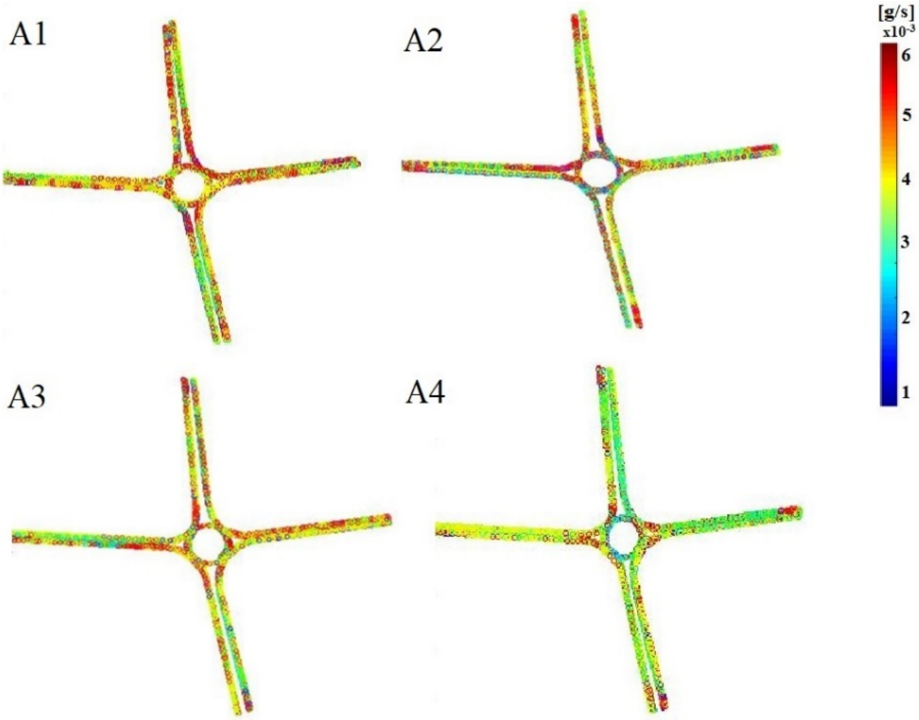
Figure 7. An example of the speed and acceleration profile of a selected vehicle when passing through a modelled two-lane roundabout (passing through South-North relation).



(a) CO_2 emission

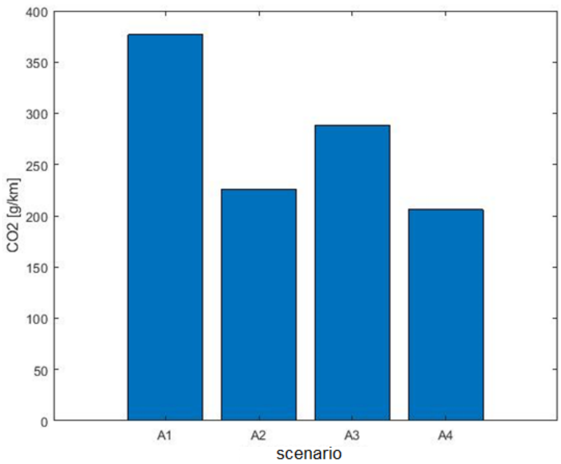


(b) THC emission

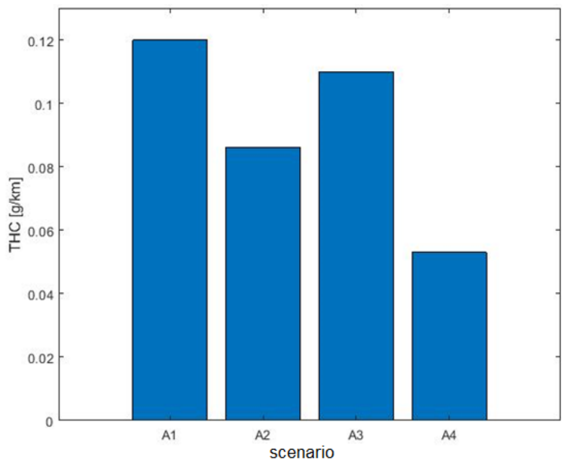


(c) CO emissions

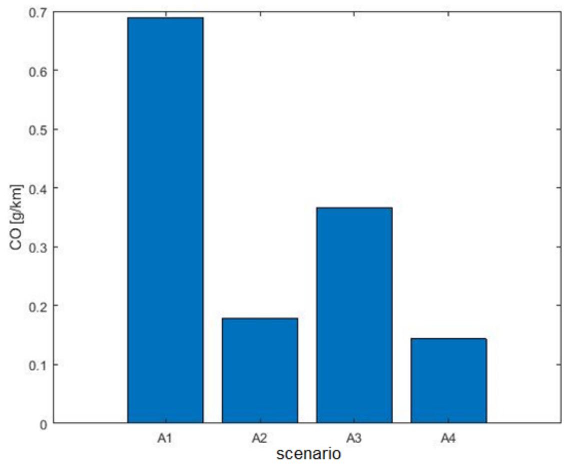
Figure 8. Emissions at the roundabout for the researched scenarios using the RoundaboutEM model.



(a)



(b)



(c)

Figure 9. Total (a) CO_2, (b) THC and, (c) CO emissions at the roundabout for the researched scenarios.

Based on emission maps and emission graphs it can be seen that the highest CO_2 emission occurs for a two-lane roundabout during morning peak hours and it exceeds the emission for a turbo roundabout by about 23% (Figure 9(a)). The maximum CO_2 emission values occur in the area of access to roundabout inlets, as well as locally on the roundabout (Figure 8(a)); the smallest CO_2 emissions occur for scenarios A2 and A4 for both roundabouts during evening hours; the emission difference for these cases is around 9% in favour of the turbo roundabout (Figure 9(a)).

In terms of THC emissions, the largest emission difference regarding the comparison of both roundabouts is for off-peak hours and is about 62% in favour of a turbo roundabout; for high traffic hours it is about 2% in favour of a turbo roundabout (Figure 9(b)). The largest amounts of THC are produced in the area of low speed travelling on the access to the roundabout as in Figure 8(b).

CO emissions are mainly associated with the rapid acceleration of vehicles; the highest CO emission values occur on access and outlets to/from roundabouts (Figure 8(c)), where acceleration occurs. The difference for a two-lane roundabout and a turbo roundabout in the morning traffic rush hours is large and amounts to approximately 88% in favour of a turbo roundabout. The difference is smaller for evening hours with less traffic and is approximately 25% with a predominance for a turbo roundabout (Figure 9(c)). The emission of the analysed harmful exhaust components is directly related to the number of stops, speed of travel and acceleration of vehicles. When the traffic volume is high, the movement parameters of the vehicle automatically deteriorate. The differences in exhaust emissions for the researched period of the day for the currently operating two-lane roundabout are as follows: for CO_2 - 66%, THC - 39%, CO - 280%, in favour of the evening hours. Regarding the turbo roundabout, these differences are as follows: for CO_2 - 29%, THC - 61%, CO - 61% also in favour of hours with less traffic.

The use of appropriately calibrated roundabout simulation models already allows estimating the emission generated at the roundabout and its surroundings, which allows better location, e.g. pedestrian crossings and the closest pavements. On the example of attached emission maps and analysed scenarios, we can observe to what extent the emission of harmful exhaust gases of vehicles would be reduced if a different roundabout solution was used. Knowledge about roundabout emissions visible from emission maps is related to the location of the highest emission spots. In the case of heavy vehicle traffic, increased emissions can be seen on all inlets to this type of intersection, generally the closer to the roundabout, the greater the sum of emissions. Also, at the entry and exit points from the roundabout, it can be noticed high emissions of CO_2, CO and THC because these are places of rapid acceleration of vehicles.

Based on the simulation results, it can be concluded that replacing the currently operating two-lane roundabout with a turbo roundabout would reduce CO_2 emissions by 20% and CO emissions by 80%. Such ecological analysis before starting the modernisation or construction of a given intersection could contribute to a significant reduction of harmful gases to the environment. Further work on such simulations and their development can be used to create new guidelines for roundabout design. The current roundabout design guidelines describe environmental problems to a marginal extent [50-53].

Figure 10(a) shows an example of the universal use of the presented simulation models and emission models for roundabouts. It shows the CO mass emissions as a function of the road travelled, for simulating a two-lane roundabout under low traffic conditions. The emission of other exhaust components, also for the turbo roundabout, shows a similar pattern. The graph shows that within the stopping area, before entering the roundabout, there is a sudden increase in emissions as a result of deceleration and subsequent acceleration from zero speed. For the tested model, vehicles crossing the yield sign line emit 33% more of CO mass than whose standing in the queue before entering the roundabout. Figure 10(b) shows the mass of CO emitted under high traffic conditions. Unlike Figure 10(a), there is a sharp increase in emissions from the moment when vehicles enter the access area to the model of the roundabout, which is mainly due to congestion and many stopping and acceleration cycles. When vehicles enter the roundabout, the increase in emissions is smaller because there is continuous travel without stops. In this case, however, vehicles that queue at the entrance to the roundabout emit 300% more CO mass than those that cross the yield sign and are driving around the roundabout.

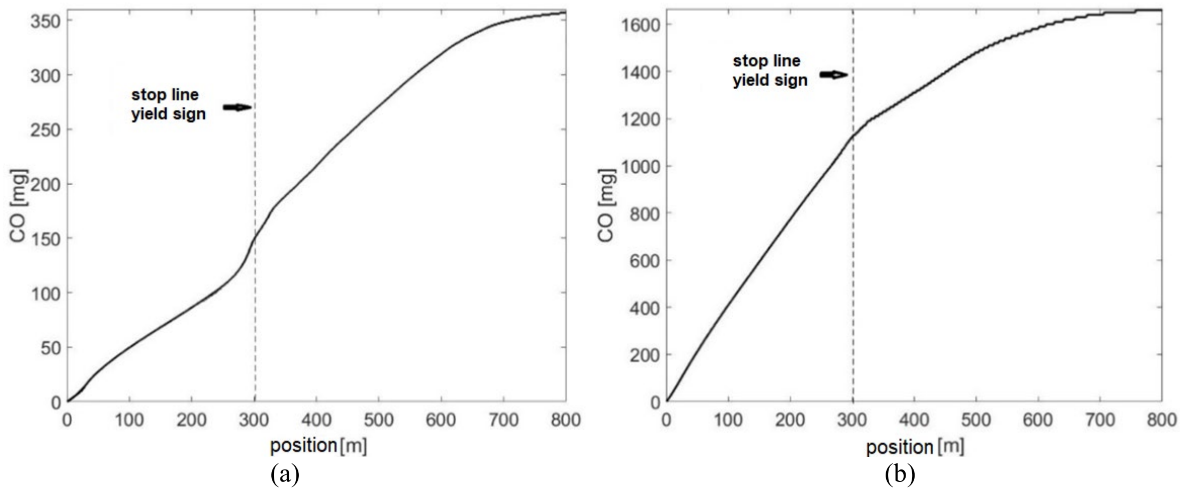


Figure 10. Mass of CO emitted as a function of the travelled road for a two-lane roundabout in (a) low traffic conditions (scenario A2) and, (b) heavy traffic conditions (scenario A1).

Figure 11. shows the dependence of CO_2 emissions on the length of the queue at the inlet to a two-lane roundabout. The growing trend is similar for the other researched exhaust components, also for the turbo roundabout solution. The figure presents data for individual emissions from all vehicle data, which is why a large number of them filled practically the entire area on the chart. To determine the emission trend, linear regression was also used. A value of 0 m length shows the situation where there is no queue and vehicles are passing freely through the roundabout. The length of the queue on the axis ends at 300 m because this is the length of the analysed roundabout inlets. Based on the presented linear regression, it can be seen how the emission of the exhaust component, in this case, CO_2, changes dynamically as the queue length increases. It is affected by the traffic conditions at the roundabout. Along with the increase in congestion, the vehicle traffic characteristics change, i.e. it has a large impact on the speed and acceleration parameters, which directly translates into emissions.

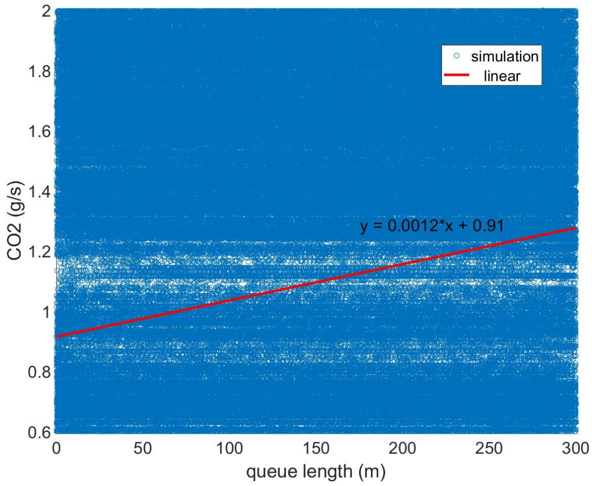


Figure 11. CO_2 emissions as a function of queue length from the simulation.

CONCLUSION

The use of properly calibrated vehicle movement simulations and emission models can be useful at the stage of performing the concept of intersection design. This is an extremely important issue because the development of technology to reduce exhaust emissions from vehicles, also should move to the level of emission reduction for road solutions, e.g. roundabouts. A better understanding of the phenomenon of vehicle exhaust emissions within roundabouts allows a better distribution of pedestrian crossings to minimise the harmful effects on the health of pedestrians. At the intersection design stage, simulations and data obtained from them are the only options to estimate the quantity of exhaust emissions.

The analysis carried out in the scope of the evaluation of harmful exhaust components emission from simulations on roundabouts indicate:

i. the need for model calibration, because lack of this activity causes inaccuracies in estimating the harmful exhaust components emission,
ii. the possibility to reduce CO_2 emissions approximately by 20%, CO by 80%, and THC by 1.1% by modification of researched two-lane roundabout into turbo roundabout, according to the analysis results,
iii. the increasing of mass of CO emissions by 300% at the inlet to the roundabout comparing to the rest of the analysed area for heavy traffic conditions,
iv. the increasing of the mass of CO emissions approximately by 33% after entering the roundabout comparing to the emission from vehicles driving on inlets for low traffic conditions,
v. the possibility of creating the simulation results based mathematical models that can be used to identify the amount of harmful exhaust components emissions in relation to the length of the queue at the inlet to the roundabout,
vi. the possibility of using emission results from roundabout simulation models for better understanding the phenomena of vehicles' emissions at such intersections,
vii. the possibility of using the developed emission model (RoundaboutEM) to analyse the harmful exhaust components emission from the existing state and possible use to design the modernisation of the current roundabout construction for improving the environmental conditions.

The described analyses and their results are valuable inputs for the development of new roundabout design guidelines. The discussed topic has great development potential and should be continued with further analysis of other types of roundabouts, in terms of diameter, number of inlets, as well as the structure itself. Further improvement should also apply to the vehicle engines exhaust emissions calculation models because engines and vehicle construction are subject to continuous improvement, which affects generated emissions [54,55].

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