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ASSESSMENT OF VEHICLE EMISSIONS AT ROUNDABOUTS: A COMPARATIVE STUDY OF PEMS DATA AND MICROSCALE EMISSION MODEL

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Abstract:

Energy efficiency has a central role to play in achieving decarbonisation targets in the transport system by changing the demand for mobility (eg. by influencing on peoples behaviors) and improving the performance of the fleet. In recent years there has been an increase of use of private transport, partly due to the recent pandemic and the reduced choice of public transport. People's travel habits have changed in frequency and motivation due to the reduced number of seats on public transport, due to social distancing but also due to online education and teleworking. This increase of use private cars has led to an increase in environmental emissions as a result of the high proportion of vehicles with combustion engines in urban areas. The highest concentrations have been recorded at road intersections and in particular at roundabout configurations where there is a higher number of stop-and-go's overall. The increasing importance of air pollution from vehicle traffic has suggested that environmental considerations should be added to these aspects as a criterion for intersection design. Several studies in the literature analyze the environmental emissions generated by vehicle traffic using different methods such as on-site recording, mathematical modeling of dispersion phenomena, micro-simulation of vehicle traffic, use of appropriately equipped vehicles with sensors. This paper presents a comparison between the results obtained from the Portable Emission Measurement System (PEMS) and the results obtained from the VERSIT+ emission model. Specifically, using a Portable Emission Measurement Systems (PEMS) installed on a series of test cars, instantaneous CO_2 and NO_X emissions were measured on repeated trips along two-lane roundabout intersections. The study was carried out by examining a selected two-lane roundabout in the city of Rzeszow (Poland) using 9 different vehicles fueled by petrol, diesel, and LPG. The results show that the investigated VERSIT+ emission model used led to an inaccuracies in the calculation of CO_2 and NO_x emissions. Furthermore, current micro-scale emission models may not estimate emissions of harmful exhaust components with sufficient accuracy due to the specificities of roundabout driving. Therefore, there is a strong demand for the development of new emission models, adapted to the driving behavior of drivers appropriate for different infrastructure objects such as roundabouts.

Keywords: *vehicle emission, roundabouts, emission modeling, micro simulation, PEMS*

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1. Introduction

Transport is one of the main economic sectors that cause environmental pollution and climate change. Emissions from transport, mainly road transport, contribute significantly to the amount of greenhouse gases in the atmosphere (Jacyna et al., 2021). In fact, the automotive sector is the second largest CO_2-producing sector with a total global contribution of 22% (Andrych-Zalewska et al., 2021).

The continuous increase in the number of motor vehicles and the limited emission control technologies make transport the major source of air pollution, especially in cities. This issue is a common problem in most of the world's agglomerations.

As a consequence of the global spread of the coronavirus, daily mobility habits have changed significantly worldwide. People are avoiding using public transportation such as buses, trains, and carpools across the globe – in Asia more so than in Europe. This benefits private transportation. Private cars and bicycles are the preferred modes of transportation (Barbarossa, 2020; Campisi et al., 2020; Tarasi et al., 2021).

While the propensity to use a private vehicle has increased, a study of five major European markets has highlighted a sharp decrease from 2019 to 2020 in vehicle registrations and purchases (Campisi et al., 2021). This issue was related to the COVID19 pandemic situation that caused an economic crisis and influenced the supply chain.

This situation has had a major impact on consumer habits regarding vehicle purchase and use, and two different trends will be compared: the preference for private car use and the economic situation. However, since the end of 2020, there has been an improvement in Europe with a slight increase in purchases of electric vehicles. Renewing the car fleet is always a positive factor for body and paint shops, as the readiness to repair dents and scratches on a car is inversely proportional to its age (de Vet et al. 2021).

From an infrastructure point of view, intersections are one of the critical points where the greatest accumulation of vehicle traffic occurs in cities. In recent years, a significant increase in the construction of roundabouts has been observed (Macioszek, 2015). The advantage of using this type of road solution is the increase in traffic safety compared to other types of intersections (Severino et al., 2021). The traffic characteristics of vehicles passing through this type of intersection are specific because the geometry of the roundabout forces drivers to brake when approaching and to accelerate when entering and leaving the roundabout envelope. With a large number of vehicles wanting to cross the roundabout at the same time, congestion occurs, resulting in many stop-and-go situations and acceleration when approaching the envelope. Congestion at roundabout entrances generally results in longer delays, longer queues, and changes in traffic speed cycles. The occurrence of these phenomena has a great impact on air quality in the area immediately surrounding roundabouts.

The results of this work present the comparison of emission obtained from PEMS for the real-world vehicle journeys and the emission from micro-emission model for the selected roundabout in the Rzeszow city (Poland). The choice of this city and this roundabout as a research study is justified by the congestion conditions that occurs at this intersection that is causing difficult environmental situation. In the city, a small number of inhabitants use public transport services and electric and hybrid vehicles are negligible in the overall fleet in the city. The novelty of the study is based on the thesis that actual micro-emission models are not adequate to properly estimate the emissions that come from vehicles at roundabouts. This will be one of the very first studies in which a research result comes from PEMS for 22 journeys on selected two-lane roundabouts for 9 different vehicles compared with the results from the micro emission model. The choice of researched vehicles is borne out by the region's statistics on vehicle ownership against emissions standards.

The aim of this work is to show how the use of actual micro-emission models can lead to inaccuracies of emission estimation for the roundabout calculation purpose. In the first part, there is a literature review of the investigated topic, and the second part includes the description of the research methodology and the results. The results show the difference of emissions for investigated vehicles and the outputs from the VERSIT+ emission model.

2. Literture review

The study of road intersections has over the years taken into account variations in conventional and non-conventional geometric patterns and different traffic composition. According to the definition, a roundabout is an intersection with a center island and a one-way carriageway around the island where vehicles go around the center island in a counter-clockwise direction in countries with right-hand traffic or in a clockwise direction in countries with left-hand traffic (Ahac et al., 2021). An exception to such movement rules are mini roundabouts, where long vehicles are allowed to pass through the traversable island (Deluka et al., 2018).

The basic features of modern traffic roundabouts include (Wu et al., 2021):

- traffic channelization,
- priority control at all inlets,
- enforcing the movement of all vehicles around the central island,
- reduction of vehicle speeds by appropriate geometric parameters.

Roundabouts have been in continuous operation for more than 100 years, while there are still debates on which type of roundabout is best in terms of capacity, safety, environmental, and geometric factors. These intersections continue to evolve from single-lane, two-lane roundabouts to new developments such as turbo roundabouts (Tollazzi et al., 2014).

Roundabout intersections are being used more and more, and as a result of their increased popularity, there are now many different solutions and their modifications; Traffic engineers study roundabouts for many parameters, mainly traffic safety and capacity at the different entrances, while the issue of vehicle emissions is mostly neglected,

Motor vehicles are the main source of pollutant emissions in urban areas (Izdebski et al., 2021; Ximinis et al., 2022). They originate from the combustion of either liquid or gaseous fuels. The main groups of emission components, due to their origin and formation process, include (Lv et al., 2022; Gis et al., 2021; Szałek et al., 2021):

- products of high-temperature processes, including nitrogen oxides (NO_x),
- incomplete combustion products, including particulates (PM), carbon monoxide (CO), and hydrocarbons (THC),
- combustion products from waste fuels, including heavy metals and sulfur oxides (SOx)
- products from other sources, such as hydrocarbon evaporation (VOC),
- products of total combustion that generate the greenhouse effect (CO_2).

The estimated value of the contribution of the emission of harmful components of exhaust gasses from vehicles to the total emission in the areas of urban agglomerations is presented in Fig. 1.

To date, few articles have been found in the literature on the comparison of vehicle emissions for roundabout-type intersections (Vasconcelos et al., 2014; Varhelyi et al., 2002). It is more common to find papers related to the comparison of other parameters such as throughput, driving safety, and time losses that occur when driving through roundabouts (Fortuijn, 2009; Giuffre et al., 2009; Giuffre et al., 2012; Mauro et al., 2010). Given the above there is a need to analyze in more detail the environmental issues related to the roundabouts.

A brief review of these studies is presented in this section, preceded by references to some articles analyzing the relationship between emissions and vehicle dynamics.

In particular, some considerations on the diffusion of the combined modeling approach to traffic microsimulation and vehicle emission models are reported, while others are based on direct field collection of emissions data, typically using portable emission measurement systems (PEMS).

2.1. Studies on the relationship between emissions and vehicle dynamics

The classification of traffic and exhaust emission models is divided according to the scale of accuracy into: macroscopic, mesoscopic and microscopic (Mądziel et al., 2022). Macroscopic emission models can be used in regional scale, mesoscopic in local scale and microscopic models can be used for the intersections purposes (roundabouts, traffic signal intersections etc.) (Qi et al., 2004).

Emission models can be divided into two categories (Sierpiński, 2012):

- models that use traffic parameters such as acceleration, braking, continuous driving and idling,
- models that are based on the average speed parameter.

Macroscopic models are used to estimate fuel consumption and the environmental impact of road transport. Macroscopic models are based mainly on the parameter of the average driving speed on the analyzed road section/s (Zhu, 2014). They make it possible to determine the impact of total energy consumption by projects and road infrastructure development strategies and to assess the impact of greenhouse gas emissions on the study area. Macroscale emission models allow for the determination of large-scale (regional, transport corridor) transport impacts.

An example representative of macro-scale emission models is the COPERT model (Bebkiewicz et al., 2021). It is based on European data using: kilometrage, vehicle structure, driving speed and air humidity and temperature. The calculation of emission factors is done for the following vehicle categories (Ntziachristos et al., 2009):

- passenger cars,
- vans (<3.5t),
- trucks (>3.5t),
- mopeds and motorbikes.

Emissions in the COPERT model are calculated according to equation (1):

$$E_i = \sum_j \left[\sum_m \left(FC_{j,m} \cdot EF_{i,j,m}\right)\right] \quad (1)$$

where:

E_i – emission of exhaust component I (g);

$FC_{j,m}$ – fuel consumption for a given vehicle category j, using fuel m (kg);

$EF_{i,j,m}$ – fuel consumption, emission factor of component i for vehicle category j and fuel m (g/kg).

Microscopic emission calculation models require a large amount of data based on continuous measurement of basic vehicle parameters such as: speed, acceleration, terrain gradient, position coordinates. They calculate instantaneous emissions over a specified unit of time, usually 1 (s). Many microscale models have been developed that calculate emissions from the results of traffic microsimulation models based on: measurement of power, speed and combinations of these parameters.

A general division of micro-scale exhaust emission models, due to the data used, includes models based on (Ahn et al., 2002; Barth et al., 2006; Ligtering et al., 2012; Rakha et al., 2011):

- speed profile: VSP, VT, Versit+,
- vehicle power: CMEM, VT-CPFM, CSIRO.

A detailed example of a microscale emission model can be the Vehicle Specific Power (VSP) model, which is defined as the engine power output per unit vehicle mass and expressed as a function of vehicle speed, road slope and acceleration (2) (Frey et al., 2006):

$$VSP = 1{,}1V\alpha + 9{,}81\theta \cdot 0{,}132V + 0{,}000302V^3 \quad (2)$$

where:

VSP – characteristic power of the vehicle (kW/t);

V – vehicle speed (km/h);

α – vehicle acceleration (m/s^2);

θ – gradient of the road (%).

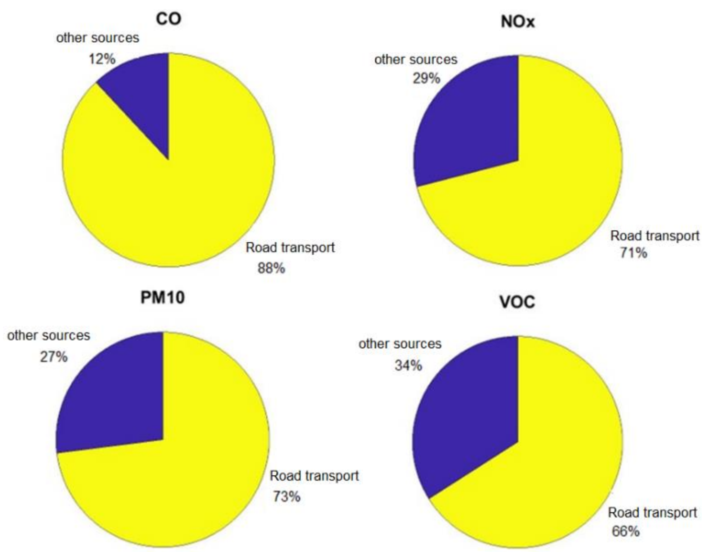

Fig. 1. Share of emissions of selected pollutant components from motor vehicles in comparison with other sources in urban centers; based on (Weiss et al., 2011; Zhu, 2014)

2.2. Studies on vehicular emissions at roundabout intersection

Most of the work on exhaust emissions at roundabouts concerns the application of models already existing to calculate exhaust emissions. In this respect, the use of computational models is considerably limited because macroscale models are not suitable for studying microscale objects such as roundabouts. The differences resulting from the use of existing models versus actual emissions will be presented in this work.

In the literature published so far, few papers can be found on the comparison of vehicle emissions for different roundabout intersection solutions. It is more common to find papers related to the comparison of other parameters such as throughput, driving safety, and time losses that occur when driving through roundabouts. The work (Mądziel et al., 2021a) is concerned with the presentation of PM concentrations generated when driving through a roundabout for high traffic volume conditions and low traffic volume conditions for simulation results. The paper (Mądziel et al., 2021b) presents the differences resulting from the application of different roundabout geometries (two-lane and turbine roundabouts) and the influence of this parameter on the emission of the selected components of exhaust gasses also for simulation results. The use of PEMS for the analysis of emissions at roundabouts is presented in papers (Gastaldi et al., 2017; Liu et al., 2017; Meneguzer et al., 2017). The works (Gastaldi et al., 2017; Meneguzer et al., 2017) refer to the comparison of functioning intersection with traffic lights to a modernized roundabout type intersection. The authors made 396 trips through both intersections using two different drivers and at different times of day. The study showed reduced CO_2 emissions for the roundabout compared to the intersection with traffic lights. However, NO_x emissions increased to the disadvantage of the roundabout. The work (Liu et al., 2017) carried out an evaluation of exhaust emissions at single-lane roundabout entrances using a PEMS apparatus and an OBDII (On Board Diagnostic) system. However, the main limitation of this work was the run using only one vehicle and measuring only CO_2.

2.3. Studies on PEMS development

Portable Emission Measurement Systems, or PEMS, are installed in cars and measure combustion engine emissions in the real world. PEMS offer a modern and innovative counterpart to controlling the impact of combustion engine emissions on the environment. PEMS used for emissions regulation integrate advanced gas analysers, exhaust mass flow meters, meteorological station, global positioning system (GPS) and connection to vehicle networks. PEMS provide comprehensive and highly accurate real-time monitoring of pollutants emitted by engines (HC, CO, CO_2, NO_x [or NO + NO_2], PM) together with associated engine, vehicle and environmental parameters. They have been around since 1990 and are very easy to transport and mount on board and are economically viable.

Several tests can be done more quickly, by fewer workers, dramatically increasing the amount of testing done in a given period of time. This, in turn, significantly reduces the 'cost per test', but at the same time increases the overall accuracy required in a 'real world' environment (El-Shawarby et al., 2005).

Thus, repeatability, predictability and accuracy are improved while simultaneously reducing the overall cost of testing.

In general, on-road vehicle emission testing is very different from laboratory testing: PEMS can be implemented on a large number of vehicles in a relatively short period of time and at relatively low cost. Different types of engines can be tested even without 4-wheel vehicles. Real world emission data can be obtained. The instruments are usually small, light, and suitable for a harsh environment and must not pose a safety hazard.

Emissions data are subject to considerable variation, as real-world conditions are often neither well defined nor repeatable, and significant variations in emissions can exist even between otherwise identical engines. On-road emissions testing therefore requires a different mindset from the traditional laboratory testing approach and the use of models to predict real-world performance. In the absence of established methods, the use of PEMS requires a careful, considered and broad approach.

Several studies in the literature have reported comparisons between Portable Emissions Measurement Systems (PEMS) with Laboratory Grade Equipment (Varella et al., 2018).

Only a few studies have addressed the differences found between PEMS and laboratory equipment for the latest generation of RDE-compliant PEMS. In some cases, the differences were high and exceeded the permissible tolerances (Czerwinski et al., 2016). A detailed analysis using two PEMS simultaneously, comparing them with both the legislative method and laboratory analysers at discharge was conducted by (Varella et al., 2018).

On the road, environmental and driving conditions can vary over a wide range, sometimes resulting in higher emissions than those measured in the laboratory (Pielecha et al., 2020).

For this reason, the European Commission has developed a complementary Real-Driving Emissions (RDE) test procedure using Portable Emissions Measurement Systems (PEMS) to verify emissions of gaseous pollutants and particle numbers during a wide range of normal operating conditions on the road. It is therefore necessary to pay particular attention to six steps, namely: 1) vehicle selection, 2) vehicle preparation, 3) trip design, 4) trip execution, 5) trip verification and 6) emissions calculation (Giechaskiel et al., 2016).

The study was conducted by comparing the emissions measured by a Portable Emission Measurement System (PEMS) sensor system housed in 9 different vehicles driving through selected two-lane roundabout located in Rzeszow (Poland). These results were compared with those obtained from a calculation approach using VERSIT+ emission model. The input parameter for the emission model were the same speed profiles that were obtained from road tests. The comparison concerned CO_2 and NO_x emissions, since these two emission factors are considered in the emission model. The calculation model was appropriately calibrated for comparison with specific vehicles complying with EURO 2 - EURO 6 standards. The general overview of the research is presented in Fig. 2.

3. Methodology of the research

The main objective of the research was to compare the real-world emissions measured by PEMS installed in different cars driving through researched roundabout with the emission obtained from emission model, in this case VERSIT+. The input values for emission calculation to VERSIT+ were also speed profiles obtained from the PEMS test. The purpose of this comparison is to show if some micro-emission models are suitable to accurately estimate the emission values, since this kind of calculations sometimes is used at the design stage of the intersection and e.g., emission estimation for different intersection geometries can give some key information for the city authorities to choose the best option. General scheme of the research methodology is presented in Fig. 3.

For real road tests, a PEMS system was used, which is owned by the Department of Combustion Engines and Transport of the Rzeszów University of Technology. PEMS systems are equipped with the following sensors for measurement of pollutants in exhaust gasses: flame ionization detector (FID) for THC measurement, nondispersive infrared spectrometer (NDIR) for CO and CO_2 measurement, and chemiluminescent analyzer (CLD) for NO and NO_2 measurement. Selected technical parameters of the used PEMS are described in Table 1.

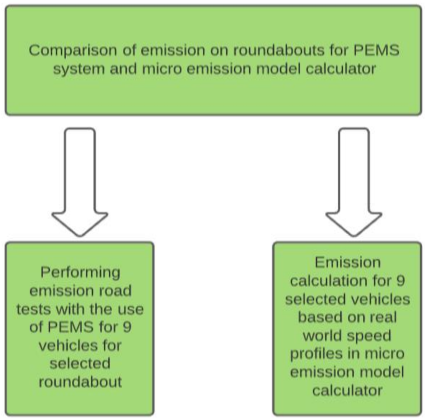

Fig. 2. General scheme of the research

To collect data on the emission of harmful components of exhaust gasses, in the first stage of the work, a road test was selected, on which emission values were recorded. The data from the actual runs were then used for comparison purposes with the VERSIT+ emission model calculator. The VERSIT+ speed profile-based emission model used in Enviver is a multivariate regression model in which the driving cycle of a given vehicle is a variable. It requires that speed profiles be obtained in advance in Vissim, from which emission factors (g/km) can be estimated for different vehicle classes (Smit et al., 2008). Road transport exhaust emissions (g/h), for a specific exhaust component of one or more road sections, are calculated from equation (3) (Smit et al., 2006):

$$TEj = \sum k,m(EF_{j,k,l} \cdot TV_{k,m} \cdot L_m) \quad (3)$$

where:
$EF_{j,k,l}$ – average emission factor (g/km);
j – exhaust emission component;
k – vehicle class;
l – speed profile;
$TV_{k,m}$ – road traffic volume (vehicles/h);
m – road section;
L_m – length of road section (km).
Since VERSIT+ requires vehicle speed profiles from Vissim, in order to fit the real-world data from PEMS journeys, there has to be done adjustment of the data log file. The raw data from PEMS is just the data for the emission exhaust component in the column, along with the speed, time etc. data, so this kind of data has to be previously accordingly prepared, since VERSIT+ has been created for the Vissim simulation output data. Exampled part of the file adjusted to the VERSIT+ emission model calculator is shown in Fig. 4.

3.1. Description of the study site

The research road in the city area includes selected two-lane roundabout which crosses national main roads entering and exiting the city. The PEMS tests were conducted during off peak hours to minimize the congestion effect on the data. Congested roundabout would make the obtained data useless. The choice of considering the roundabout is based on the fact that this roundabout has one of the highest volumes of vehicles in the city and is one of the main roundabouts and can be considered as a representative. The route adopted for the study including a researched two-lane roundabout is shown in Fig. 5. The researched roundabout has 4 inlets and outlets. The dimension of the road width for inlets and outlets is 4.15m, and for road at the roundabout 4.28m. The main flow direction is in the relation of the north-south, which is why the journeys were made according to this flow. Each of the researched vehicles made 2 journeys through the roundabout with the installed PEMS. As two vehicles are bi-fuel, the total number of runs was 22 trials. This was a sufficient test sample to determine the average vehicle speed profile and to calculate emissions. The considered path to the inlet and outlet of the roundabout was limited to 300 m.
Such a choice of vehicles was justified by the fact that, according to statistical data (Polish Local Data Bank, 2020), the number of passenger vehicles meeting the relevant EURO standards in 2025 will be as follows: for EURO 2 - 7%, EURO 3 - 16%, EURO 4 - 31%, EURO 5 - 23%, EURO 6 - 18%. Other emission classes will account for less than 5%. In the next few years, due to the possibility of introducing further restrictive regulations regarding the entry of cars with combustion engines into city centers, the number of new vehicle designs may increase. The work is essentially concerned with passenger vehicles, as it mainly refers to infrastructure facilities inside cities (roundabouts), where the number of passenger vehicles is clearly dominant.
All the vehicles tested were checked using stationary exhaust gas analysers prior to the tests, in accordance with the test procedure for periodic diagnostic tests. The results of concentrations and amounts of harmful components of exhaust gasses of the tested vehicles were within permissible limits.

Table 1. Selected technical parameters of the PEMS Horiba OBS-2200 system

Parameter	Measurement method	Accuracy
The concentration of exhaust components:		
CO	NDIR - non-dispersive (infrared), range 0-10%	±2,5%
CO_2	NDIR - non-dispersive (infrared), range 0-10%	±2,5%
THC	FID - flame ionization, range 0-10000 ppm	±2,5%
NO_x	CLD - chemiluminescence, range from 0-100 to 0-3000 ppm	±2,5%
Sampling frequency	1 Hz	
The heating time of the analyzers	Up to 1 hour	-
Gas flow	Mass flow rate	In the range of ± 1.5% of full scale or within ± 2.5% of readings

The researched roundabout has at its inlets and outlets the set of road sensors (induction loops and cameras) to count the vehicle number, so that means that the priority of the local authorities is to measure the vehicle number and analyze the intersections data to have more environmental look how the traffic looks like on them.

The tests were carried out in 2019 and 2020 using 9 cars, under comparable temperature conditions. The vehicles tested are shown in Figure 6. The EURO 3 vehicle was fitted with an LPG system, so two road tests were conducted using this car, one for petrol and one for LPG. Two road tests were also conducted for the EURO 6 car (1), as it had a factory-fitted LPG system. All petrol cars, with the exception of EURO 5 (1), had multipoint injection (MPI) and were therefore fitted with trifunctional catalytic reactors as standard.

The engines of EURO 5 (2) and EURO 6 (3) vehicles use downsizing technology, i.e., they are mechanically supercharged, which increases their power output, resulting in parameters comparable to engines of a larger capacity without supercharging. In addition, this solution reduces fuel consumption and vehicle weight. The EURO 6 car (2) is powered by a diesel engine.

The work covers passenger vehicles, as it mainly refers to infrastructure facilities inside cities (roundabouts), where the number of passenger vehicles is clearly dominant.

To compare the emissions obtained from the PEMS system and the emissions from the model, the Enviver program was used to calculate the emissions on a microscale. This model was chosen for the calculations because it is one of the few suitable for simulating exhaust emissions for infrastructure facilities. The variable to be entered into this model is the driving cycle that contains speed data as a function of time. In addition, the model allows emissions to be calculated as a function of the terrain gradient. Ultimately, Enviver will take Vissim driving cycle data from the Vissim traffic microsimulation program as input. To evaluate the emission model in this study, exhaust emission data from the PEMS system were used from travels made on the study route at roundabout.

The comparison consisted of setting the fuel type, emission classes, and road data in the software as for the real trip, and the driving cycle from the tested route was entered successively. An example of parameter setting for one of the runs is shown in Fig. 7.

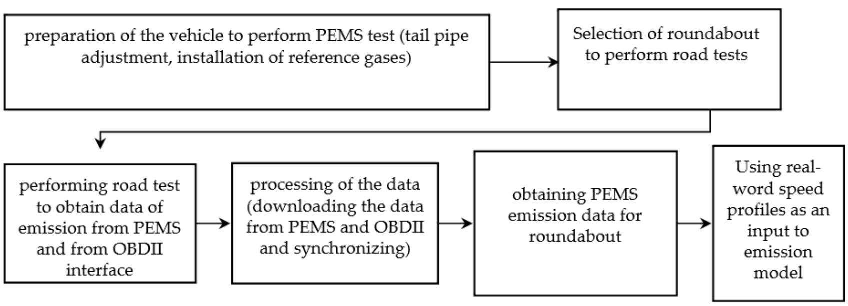

Fig. 3. General scheme of the research methodology

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$VEHICLE:COORDFRONT;NO;SIMSEC;SPEED;VEHTYPE\NO;VEHTYPE\NAME;LANE\LINK\GRADIENT;ACCELERATION;DISTTRAVTOT
54.918 121.404 0.000;601;900.10;43.36;100;Car;0.00 %;0.00;616.79
128.680 96.378 0.000;611;900.10;0.00;100;Car;0.00 %;0.00;324.07
124.057 99.384 0.000;659;900.10;0.00;100;Car;0.00 %;0.00;319.16
119.353 102.634 0.000;664;900.10;0.00;100;Car;0.00 %;0.00;312.42
157.159 281.375 0.000;684;900.10;40.79;100;Car;0.00 %;0.00;511.89
400.576 142.459 0.000;691;900.10;36.18;100;Car;0.00 %;0.00;517.93
441.980 152.172 0.000;692;900.10;62.46;100;Car;0.00 %;0.00;560.60
222.389 112.949 0.000;694;900.10;34.61;100;Car;0.00 %;0.76;520.63
328.474 135.244 0.000;695;900.10;51.63;100;Car;0.00 %;0.00;446.05
114.694 105.002 0.000;700;900.10;0.00;100;Car;0.00 %;0.00;307.83
197.845 143.067 0.000;701;900.10;31.78;100;Car;0.00 %;0.00;364.40
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Fig. 4. Exampled data for PEMS journeys adjusted to use in VERSIT+

Fig. 5. The researched two-lane roundabout (left) and the map of it (right; with marked outer diameter and researched area)

Fig. 6. Researched vehicles used for PEMS tests

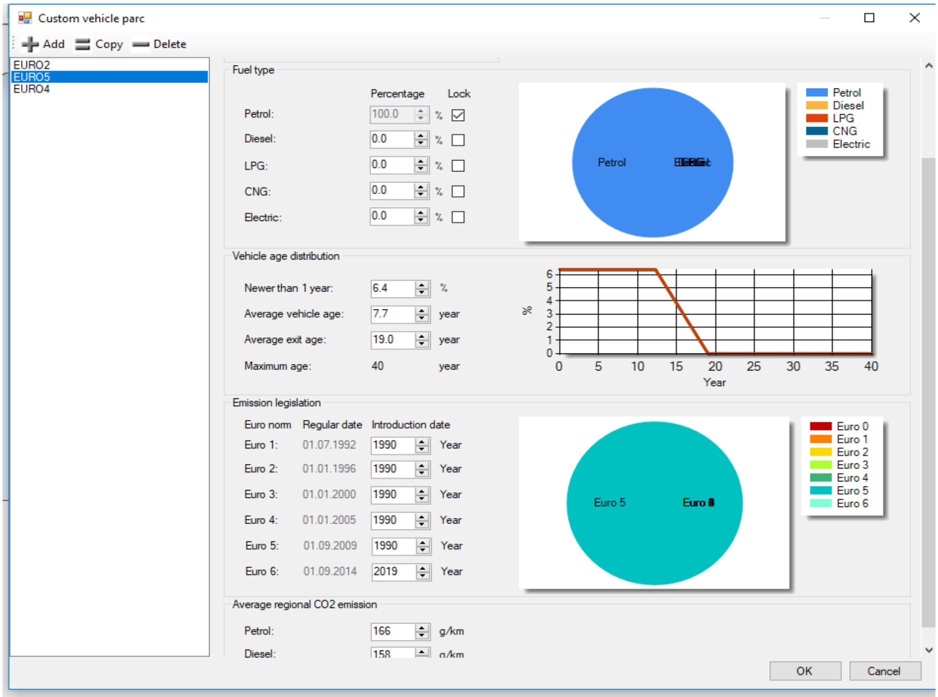


Fig. 7. Example parameter settings for Euro 5 vehicle in the VERSIT+ model

4. Results and discussion

The first stage of work assumed gathering of the PEMS data for the researched emissions and for the speed of the tested vehicles. The example road tests for the roundabout results of speed profile, and PEMS emission of CO_2 and NO_x is presented in Fig. 8. Average speed profile from the researched roundabouts is shown in Fig. 9. The roundabout envelope starts at a 300 m position.

The excluded speed and acceleration profiles from the real-word tests have been successfully adjusted to the requirements of the VERSIT+ emission model. Based on these parameters and vehicle settings, VERSIT+ calculated the emission as emission factor values (g/km).

An example of a driving cycle showing a roundabout crossing from the PEMS system in Enviver is shown in Fig. 10, while an example emission factor results for a selected vehicle roundabout journey is included in Fig. 11. A comparison of exhaust emissions from real road test from the PEMS system and the VERSIT+ model is shown in Figures 12 and 13. The VERSIT+ emission model only allows the calculation of CO_2, NO_x and PM emissions. As the PEMS system used for the study does not have a particulate matter analyser, CO_2 and NO_x emission values were used for comparison.

Based on Figure 12, which shows a comparison of CO_2 emissions from the PEMS system and the VERSIT+ model, it can be noted:

– there is no CO_2 emission data for LPG vehicles, i.e., for EURO3 and EURO6, the program indicated values of 0 g/km,
– the biggest differences of the obtained emissions concern the EURO6 (Diesel) and EURO2 vehicles; they are about 47% and 55%, respectively,
– the smallest difference is for the EURO3 vehicle (petrol); it is ca. 2%.

A comparison of PEMS tests NOx emissions to those from the VERSIT+ model is presented in Fig. 13. It can be concluded that:

– the highest emission differences occur for EURO6 (petrol), EURO4, EURO6 (LPG) and

EURO6 (diesel) vehicles and amount to ca. 5400, 2390, 1700, 1300%, respectively,

- the lowest emission differences are found for EURO3 (LPG) and EURO2 vehicles and amount to ca. 15% and 43%, respectively.

The relative differences of exhaust emissions from the actual value for the VERSIT+ model for individual vehicle models is presented in Table 2.

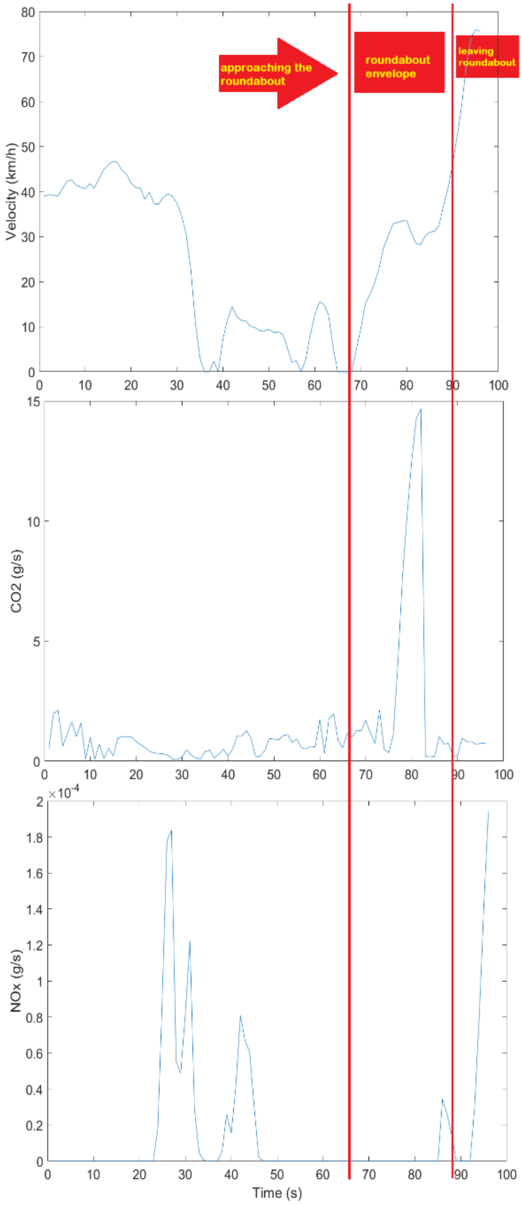


Fig. 8. Example data for PEMS journey at researched roundabout for the parameter of velocity, CO_2 and NOx emission

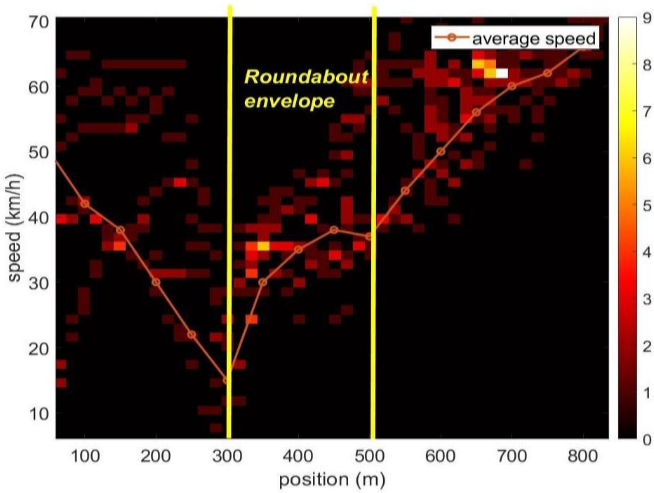


Fig. 9. Average speed profile frequency from road tests for the researched roundabout

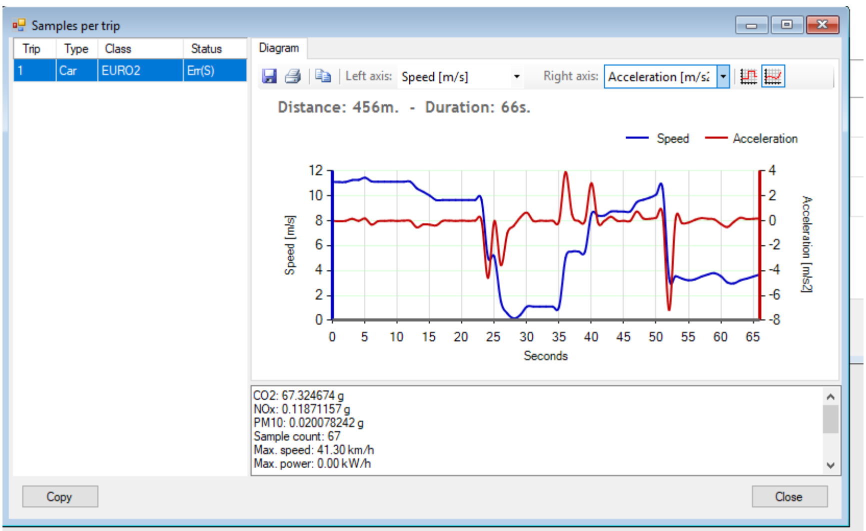
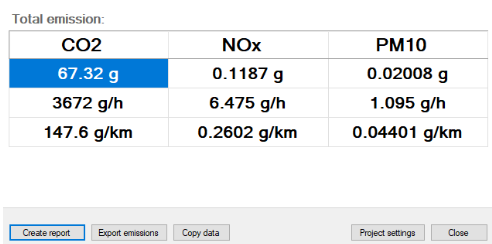


Fig. 10. Example speed and acceleration profile in the VERSIT+ model



Total emission:

CO2	NOx	PM10
67.32 g	0.1187 g	0.02008 g
3672 g/h	6.475 g/h	1.095 g/h
147.6 g/km	0.2602 g/km	0.04401 g/km

Fig. 11. Example results from the roundabout journey in the VERSIT+ model

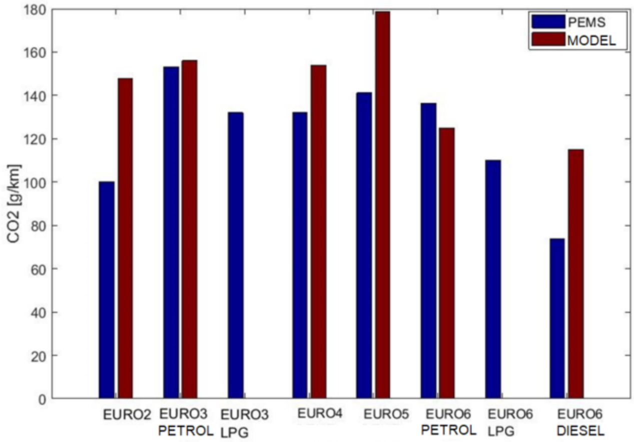


Fig. 12. Comparison of the CO_2 emission from PEMS tests and model data

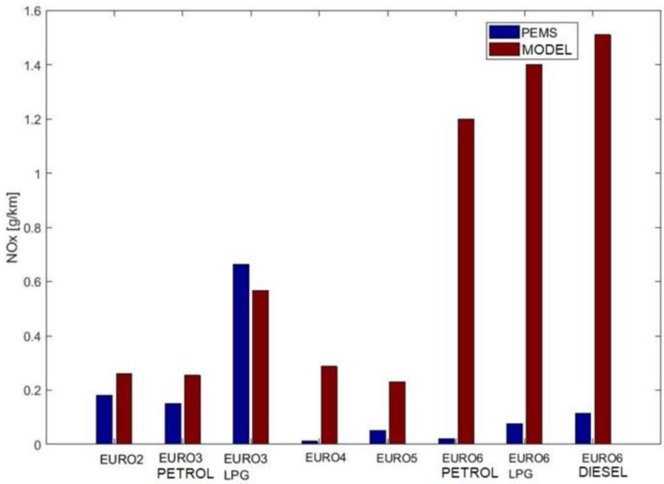


Fig. 13. Comparison of the NO_X emission from PEMS tests and model data

Table 2. Relative differences of CO_2 and NOx emissions from the VERSIT+ calculation model to PEMS emission

Vehicle type	Exhaust component	
	CO_2	NO_x
EURO2	47%	43%
EURO3 (PETROL)	2%	69%
EURO3 (LPG)	-	85%
EURO4	16%	2390%
EURO5	25%	346%
EURO6 (PETROL	8%	5407%
EURO6 (LPG)	-	1732%
EURO6 (DIESEL)	55%	1373%

Based on the Table 2 it can be seen that the relative differences are high for most of the tested vehicles. If we wanted to analyze the emissions that occur at roundabouts, using most micro-models, we would obtain discrepancies similar to those for the VERSIT+ model. Therefore, to draw some conclusions about the environmental aspect of the emissions of vehicles traveling at roundabouts, it is necessary to develop more accurate models that are sufficiently sensitive to the behaviour of drivers traveling at roundabouts. The above discrepancies may be due to the fact that most emission models are developed by research teams of a specific country, which may cause the application of such an emission model to give inadequate estimates of results for emission factors, as is the case here. These discrepancies may also result from the fact that for roundabout journeys, despite vehicle speeds and accelerations similar to those for other traffic situations outside the roundabout, different engine loads occur (different gear ratios), directly affecting the results of harmful exhaust component emissions. Therefore, it is necessary to create national emission models that will be appropriate for the behaviour of drivers in a given country. It is also important for the scale of models created, as for most emission models at the microscale we distinguish between models for urban, rural, or motorway driving characteristics, but it is worth considering whether such models should not be distinguished in greater detail, taking into account, for instance, intersections such as roundabouts. This is important because certain decisions concerning the design or modernisation of such an infrastructure solution may be taken on the basis of emission results and, in particular, on emission maps.

5. Conclusions

In the coming years, a significant increase in the number of vehicles is expected, which will worsen the condition of the environment and adversely affect the health of the population, especially in urban areas. This situation will lead to increased congestion, especially at street intersections. Therefore, it is important to be aware in road design of the environmental factors associated with the intersection solution used.

Validating calculations from an exhaust emission model is difficult because emissions depend on many factors, making one actual measurement from a road difficult to relate to the next. Based on the comparison carried out between the emissions from the PEMS system at roundabout and the emissions obtained from the calculation model, the following conditions can be concluded:

- emission models from road tests are prepared on the basis of tests conducted in a given region, which results in erroneous estimation of exhaust pollutant emissions for other areas, as the emissions in urban areas are strongly influenced by weather conditions and drivers' driving style,
- emission models based on driving cycles do not take into account such vehicle data as, e.g. gear ratio or engine load, which significantly affect the result of vehicle emissions,
- the VERSIT+ emission model contains to less data coming from LPG vehciles, which makes impossible to calculate CO_2 emission,
- based on NO_x emission results, a significant overestimation of results for EURO4, EURO5 and EURO6 vehicles may be observed, which may result from the fact that a large part of petrol vehicles included in the model had the GDI type power supply system; NO_x emission from a diesel fueled vehicle in the tested case is also overestimated and may result from the fact that the tested vehicle entered service after the period of introduction of new type-approval regulations, i.e. WLTP, and therefore had the SCR type exhaust gas after-treatment system,
- an additional limitation of the model used was the indication of emissions for only three exhaust gas components (CO_2, NO_x and PM), which does not take into account THC and CO, important components in terms of environmental impact.

In conclusion, it can be stated that the current more widely used microscale emission models, in particular the VERSIT+ model under study, may underestimate the emission values obtained at roundabout type facilities due to different driving characteristics of vehicles, i.e. different engine loads for given speeds, etc. This creates a strong demand for the development of micro-scale emission models that are sufficiently sensitive to this type of micro-behavior of vehicles for different road objects. This problem also applies to the modeling of emissions for hybrid vehicles, because micro emission models are mostly created for fully combustion engines vehicles (Mądziel et al., 2022)..

Abbreviations

PEMS - Portable Emission Measurement System;
CO_2 - carbon dioxide;
CO- carbon monoxide;
NOx- nitrogen oxides;
LPG - liquefied petroleum gas;
PM - particulate matter;
VOC - volatile organic compounds;
THC - total hydrocarbons;
VSP - Vehicle Specific Power;

OBD - On-Board Diagnostics;
WLTP - Harmonized Light-Duty Vehicles Test Procedure;
GDI - Gasoline Direct Injection.

References

[1] Ahac, S., Dragčević, V. (2021). Geometric Design of Suburban Roundabouts. *Encyclopedia*, 1, 720-743, DOI: 10.3390/encyclopedia1030056.

[2] Ahn, K., Rakha, H., Trani, A., Van Aerde, M. (2002). Estimating vehicle fuel consumption and emissions based on instantaneous speed and acceleration levels. *Journal of Transportation Engineering* 128(2), 182-190.

[3] Andrych-Zalewska, M., Chlopek, Z., Merkisz, J., Pielecha, J. (2021). Research on Exhaust Emissions in Dynamic Operating States of a Combustion Engine in a Real Driving Emissions Test. *Energies*, 14, 5684, DOI:-10.3390/en14185684.

[4] Barbarossa, L. (2020). The post pandemic city: challenges and opportunities for a non-motorized urban environment. An overview of Italian cases. *Sustainability*, 12(17), 7172.

[5] Barth, M., Scora, G. (2006). Comprehensive modal emissions model (CMEM), *User"s Guide, Version 3.01*. University of California, Riverside.

[6] Bebkiewicz, K., Chłopek, Z., Sar, H., Szczepański, K., Zimakowska-Laskowska, M. (2021). Assessment of impact of vehicle traffic conditions: urban, rural and highway, on the results of pollutant emissions inventory. *Archives of Transport*, 60(4), 57-69, DOI: 10.5604/01.3001.0015.5477.

[7] Campisi, T., Basbas, S., Skoufas, A., Akgün, N., Ticali, D., & Tesoriere, G. (2020). The impact of COVID-19 pandemic on the resilience of sustainable mobility in Sicily. *Sustainability*, 12(21), 8829.

[8] Campisi, T., Garau, C., Ignaccolo, M., Coni, M., Canale, A., Inturri, G., & Torrisi, V. (2021). A New Vision on Smart and Resilient Urban Mobility in the Aftermath of the Pandemic: Key Factors on European Transport Policies. *In International Conference on Computational Science and Its Applications* (pp. 603-618). Springer, Cham.

[9] Czerwinski, J., Zimmerli, Y., Comte, P., Bütler, T. (2016). Experiences and results with different PEMS. *J. Earth Sci. Geotech. Eng*. 6, 91–106.

[10] de Vet, J. M., Nigohosyan, D., Ferrer, J. N., Gross, A. K., Kuehl, S., & Flickenschild, M. (2021). Impacts of the COVID-19 pandemic on EU industries. European Parliament.

[11] Deluka Tibljaš, A., Giuffrè, T., Surdonja, S., Trubia, S. (2018). Introduction of Autonomous Vehicles: Roundabouts Design and Safety Performance Evaluation. *Sustainability*, 10, 1060, DOI: 10.3390/su10041060.

[12] El-Shawarby, I., Ahn, K., Rakha, H. (2005). Comparative Field Evaluation of Vehicle Cruise Speed and Acceleration Level Impacts on Hot Stabilized Emissions. *Transportation Research Part D*, 10 (1), 13–30.

[13] Fortuijn, L. (2009). Turbo roundabouts: design principles and safety performance. *Transp. Res. Rec. J. Transp. Res. Board* 2096, 16–24.

[14] Frey, H.C., Rouphail, N.M., Zhai, H. (2006). Speed-and facility-specific emission estimates for on-road light-duty vehicles on the basis of real-world speed profiles. *Transportation Research Record: Journal of the Transportation Research Board* 1987(-1), 128-137.

[15] Gastaldi, M. (2017). On-road measurement of CO_2 vehicle emissions under alternative forms of intersection control. *Transportation Research Procedia* 27.

[16] Giechaskiel, B., Vlachos, T., Riccobono, F., Forni, F., Colombo, R., Montigny, F., Weiss, M. (2016). Implementation of portable emissions measurement systems (PEMS) for the real-driving emissions (RDE) regulation in Europe. *Journal of visualized experiments: JoVE*, (118).

[17] Gis, W., Gis, M., Pielecha, J., Skobiej, K. (2021). Alternative Exhaust Emission Factors from Vehicles in On-Road Driving Tests. *Energies*, 14, 3487, DOI:10.3390/en14123487.

[18] Giuffre, O., Guerrieri, M., Grana, A. (2009). Evaluating capacity and efficiency of turbo roundabouts. *Transportation Research Board 88th Annual Meeting*, Washington.

[19] Giuffrè, O., Granà, A., Marino, S. (2012). Turbo-roundabouts vs Roundabouts Performance Level. *Procedia - Social and Behavioral Sciences* no. 53:590-600.

[20] Izdebski, M., Jacyna, M. (2021). An Efficient Hybrid Algorithm for Energy Expenditure Estimation for Electric Vehicles in Urban Service Enterprises. *Energies*, 14, 2004, DOI:10.3390/en14072004.

[21] Jacyna, M., Żochowska, R., Sobota, A., Wasiak, M. (2021). Scenario Analyses of Exhaust Emissions Reduction through the Introduction of Electric Vehicles into the City. *Energies*, 14, 2030, DOI:10.3390/en14072030.

[22] Ligtering, N., Lange, R. (2012). Refined vehicle and driving-behavious dependencies in the VERSIT+ emission model. *Environment&Transport.*

[23] Liu, et al. (2017). Characterizing the Relationship between Carbon Dioxide Emissions and Vehicle Operating Modes on Roundabouts -A Pilot Test in a Single Lane Entry Roundabout. *Environ Pollut Climate Change.*

[24] Lv, Z., Yang, L., Wu, L., Peng, J., Zhang, Q., Sun, M., Mao, H., Min, J. (2022) Comprehensive Analysis of the Pollutant Characteristics of Gasoline Vehicle Emissions under Different Engine, Fuel, and Test Cycles. *Energies*, 15, 622, DOI:10.3390/en15020622.

[25] Macioszek, E. (2015). The roads safety at roundabouts in Poland. *The Archives of Transport*, 33(1), 57, DOI:10.5604/08669546.1160927.

[26] Mądziel, M., Campisi, T., Jaworski, A., Kuszewski, H., Woś, P. 2021b. Assessing Vehicle Emissions from a Multi-Lane to Turbo Roundabout Conversion Using a Microsimulation Tool. *Energies*, 14, 4399, DOI:10.3390/en14154399.

[27] Mądziel, M., Campisi, T., Jaworski, A., Tesoriere, G. (2021). The Development of Strategies to Reduce Exhaust Emissions from Passenger Cars in Rzeszow City—Poland. A Preliminary Assessment of the Results Produced by the Increase of E-Fleet. *Energies*, 14, 1046, DOI:10.3390/en14041046.

[28] Mądziel, M., Jaworski, A., Kuszewski, H., Woś, P., Campisi, T., Lew, K. (2022). The Development of CO_2 Instantaneous Emission Model of Full Hybrid Vehicle with the Use of Machine Learning Techniques. *Energies*, 15, 142, DOI:10.3390/en15010142.

[29] Mauro, R., Cattani, M. (2010). Potential accident rate of turbo-roundabouts. *Proceedings of 4th International Symposiumon Highway Geometric Design Valencia, Spain: Transportation Research Board*.

[30] Meneguzzer, C. (2017). Comparison of exhaust emissions at intersections under traffic signal versus roundabout control using an instrumented vehicle. *Transportation Research Procedia 25.*

[31] Ntziachristos, L., Gkatzoflias, D., Kouridis, C., Samaras, Z. (2009). COPERT: A European Road Transport Emission Inventory Model. In: Athanasiadis I.N., Rizzoli A.E., Mitkas P.A., Gómez J.M. (eds) *Information Technologies in Environmental Engineering. Environmental Science and Engineering*. Springer, Berlin, Heidelberg, DOI:10.1007/978-3-540-88351-7-37.

[32] Pielecha, J., Skobiej, K. (2020). Evaluation of ecological extremes of vehicles in road emission tests. *Archives of Transport*, 56(4), 33-46, DOI: 10.5604/01.3001.0014.5516.

[33] Qi, Y., Teng, H., Yu, L. (2004). Microscale Emission Models Incorporating Acceleration and Deceleration. *Journal of Transportation Engineering* 130(3), 348-359.

[34] Rakha, H.A., Ahn, K., Moran, K., Saerens, B., Bulck, E.V.d. (2011). Virginia Tech Comprehensive Power-Based Fuel Consumption Model: Model development and testing. *Transportation Research Part D: Transport and Environment* 16(7), 492-503.

[35] Severino, A., Pappalardo, G., Curto, S., Trubia, S., Olayode, I.O. (2021). Safety Evaluation of Flower Roundabout Considering Autonomous

Vehicles Operation. *Sustainability*, 13, 10120, DOI: 10.3390/su131810120.

[36] Sierpiński, G. (2012). Theoretical Model and Activities to Change the Modal Split of Traffic. In: Mikulski, J. (ed.) TST 2012. CCIS, vol. 329, pp. 45–51. Springer, Heidelberg.

[37] Smit, R., Smokers, R., Rabe, E. (2008) A new modelling approach for road traffic emissions: VERSIT+. *Trasportation research part D*, 412-422.

[38] Smit, R., Smokers, R., Shoen, E., Hensema, A. (2006). A new modelling approach for road traffic emissions: VERSIT+ LD – background and methodology. *Report 06.ORPT.016.1/RS, The Hague*. TNO Science and Industry.

[39] Szałek, A., Pielecha, I., Cieslik, W. (2021). Fuel Cell Electric Vehicle (FCEV) Energy Flow Analysis in Real Driving Conditions (RDC). *Energies*, 14, 5018, DOI: 10.3390/en14165018.

[40] Tarasi, D., Daras, T., Tournaki, S., & Tsoutsos, T. (2021). Transportation in the mediterranean during the COVID-19 pandemic era. *Global Transitions*, 3, 55-71.

[41] The website of the Polish Local Data Bank. (2020).Available: https://bdl.stat.gov.pl. [Accessed: 21 Dec 2021].

[42] Tollazzi, T., Renčelj, M. (2014). Comparative analyse of the two new alternative types of roundabouts – turbo and flower roundabout. *Balt. J. Road Bridge Eng.*

[43] Varella, R. A., Giechaskiel, B., Sousa, L., & Duarte, G. (2018). Comparison of portable emissions measurement systems (PEMS) with laboratory grade equipment. *Applied Sciences*, 8(9), 1633.

[44] Varhelyi, A. (2002). The effects of small roundabouts on emissions and fuel consumption: a case study. *Transportation Research Part D*.

[45] Vasconcelos, L., Ana B. Silva, Álvaro M. Seco, P. Fernandes, Margarida C. Coelho. (2014). Turboroundabouts: Multicriterion Assessment of Intersection Capacity, Safety, and Emissions.Transportation Research Record: *Journal of the Transportation Research Board no.* 2402 (-1):28-37.

[46] Weiss, M. (2011). On-road emissions of light-duty vehicles in Europe. *Environ. Sci. Technol*. 45.

[47] Wu, Y., Zhu, F. (2021). Junction Management for Connected and Automated Vehicles: Intersection or Roundabout? *Sustainability*, 13, 9482, DOI:10.3390/su13169482.

[48] Ximinis, J., Massaguer, A., Massaguer, E. (2022). NOx Emissions below the Prospective EURO VII Limit on a Retrofitted Heavy-Duty Vehicle. *Appl. Sci*. 12, 1189, DOI:10.3390/app12031189.

[49] Zhu, S., (2014). Development of vehicle emission models for Australian conditions. *Doctoral thesis*, The University of Queensland, Australia.

[50] Campisi, T., Canale, A., Ticali, D., & Tesoriere, G. (2021, March). Innovative solutions for sustainable mobility in areas of weak demand. Some factors influencing the implementation of the DRT system in Enna (Italy). In *AIP Conference Proceedings* (Vol. 2343, No. 1, p. 090005). AIP Publishing LLC.