Journal of Earth Sciences and Geotechnical Engineering, vol. 7, no.1, 2017, 63-82
ISSN: 1792-9040 (print), 1792-9660 (online)
Scienpress Ltd, 2017

Measurement of Exhaust Emissions in Real driving Conditions as a Determinant for Sustainable Transport System Development

Jerzy Merkisz[1] and Marianna Jacyna[2]

Abstract
Shaping complex transport system requires tools supporting decision-making. From the one hand it is necessary to complete needs of transport system users, and from the other reducing the negative impact of transport on the environment. The paper presents an approach to analyze the impact on the designing of sustainable transport system of exhaust emissions in real traffic conditions. The authors show that developing of sustainable transport system will allow for conducting wide research, experimentation and simulation related to distribution of traffic flow on the transport network. Research can be conducted from the point of view three scales: macro, meso and micro. In the paper presents the example of research on this scales.

Keywords: exhaust emissions, real traffic conditions, sustainable transport system

1 Introduction – selected aspects of ecological transport systems

The design of the transport system development process, allowing for the limitations related to the protection of natural environment, requires the analyses to include such factors as: air pollution, land and water contamination, noise and vibrations generated by transport. The emission of greenhouse gases as the result of transport activities contributes to the climatic changes. Noise has a negative impact on human health and the natural environment. Exploitation of ecologically valuable land, its fragmentation with newly constructed technical infrastructure intensifies the loss of biological variety.
The authors of e.g. [1], [5] note that polluted air not only affects human health but also agriculture. It leads to the deterioration of forest areas, generates costs of environmental protection and medical care. Continuous actions are therefore necessary to increase awareness of and effective prevention from exhaust emissions as well as their reduction (including their dispersion).

[1]Poznan University of Technology, Institute of Combustion Engines and Transport.
[2]Warsaw University of Technology, Faculty of Transport.

In light of the above, the legislators force the engineers to design vehicles and develop relevant transport technologies and infrastructure to minimize transport's impact on the natural environment. From the other hand minimization of negative impact on the environment can be achieved by introducing proper division of tasks between the different transport modes. From the analysis of the problem [2], [9], [10], [11], [12], [14], [26] follows that in modal split between different modes of transport, namely the structure of the transport system, primarily decide economic calculation results conducted by transport users. Participants of transport process in a natural way are looking for optimal solutions regarding to meet the transport needs, where the price of the transport service is essential, but not one and only decision criterion. More often dominant factor in assessing of the usefulness of the various modes of transport, in the context of their participation in the transport, is the concept of comprehensive logistics services, including not only the transport of passengers and freight, but the whole process, which is the transport chain, from the point of origin of traffic flow to the point of destination [13].

The paper presents a model of designing proecological transport system - EMITRANSYS ([1], [2]) developed by scientists from Warsaw University of Technology and Poznań University of Technology. This model is a tool allowing for simulation research of the influence of road transport on the environment based on mathematical relations between the exhaust emissions as a function of the parameters of the road technical infrastructure and as a function of organizational solutions of the transport system and vehicle operating parameters.

A modeling framework that consistently provides both trip-based and link-based vehicle miles travelled speed distributions and quantifies the effects of using trip-based versus link-based travel data on regional peak period emission inventories is presented in [4] and [24]. For example Russo and Musolino in [24] presents the transport macro-model consisting of three main components: the transport supply model, travel demand model and the assignment model. Additionally Merkisz-Guranowska et al. in [22] describe the steps and basic guidelines related to the development of a sustainable transport systems model.

In light of the above it is very important to develop the methodology of exhaust emission measurements in the creation of sustainable road transport. In works by Jachimowski et al. [8] and Merkisz et al. [20], the authors analyze research based on real-time experiments and long-term on-board analyses in order to gain universal emission characteristics for different traffic conditions including cold starts, long and short trips or congestion. Their research was carried out to answer the question of real emission levels compared to the EURO standards. EMITRANSYS project adapts this methodology to obtain broad vehicle characteristics appropriate for simulation ([8], [11], [13], [14], [15], [17], [20], [22]).

The intention of the authors was to determine the impact of the driver's behavior on the human environment and to indicate the impact of the driving style on the environmental and energy-related aspects of the vehicle operation. Therefore, this paper presents results of exhaust emission tests (performed on a passenger car) conducted in actual traffic conditions. The tests provided information about the exhaust emissions under dynamic conditions of urban traffic. The tests were conducted for preliminary validation of the influence of the driving style on the emission of carbon dioxide and fuel consumption.

Modeling of a pro-ecological transport system, and then simulating it, requires relevant data about the exhaust emissions in transport. Road transport is the main source of pollution and it has wide coverage in literature (e.g. [6]). For NO_2, road traffic is of special relevance because it typically accounts for the major proportion of NO_x emissions, and hence the NO_2 concentrations ([20], [25]).

Most of the emission factors used by the emission inventories to quantify traffic contribution upon total emissions originate from laboratory measurements carried out according to specific measurement and driving procedures (e.g. [7]).
The proposed methodology enables defining the exhaust emissions as a function of driving speed for different emission categories of vehicles fitted with different types of engines. The book provides average values, but in special cases it will be necessary to combine the relations among accelerations, decelerations and stoppages. The accuracy of the performed analysis will depend on the adoption of generalizations such as, among others: number of non-classified vehicles and type of traffic that varies from that described in the paper.

2 Modeling of vehicle environmental performance

2.1 Definition of exhaust indexes (conformity factors)

The fundamental and at the same time practical applications of exhaust emissions measurements under actual operating conditions are:

- assessment of the impact of transport (automotive) on the natural environment, mainly used for the classification of pollutions and quantitative investigation of the sources of pollution,
- assessment of the efficiency of the initiatives related to the changes of the environmental impact of transport (modification in traffic organization, modernization of automotive legislation).

Commonly applied models of total exhaust emissions from transport have a complex mathematical structure (Corinair, Part 5, Mobile 6, Rains and Copert 5, Visum) and their characteristics and parameters depend on a very large number of quantities [19]. For these reasons, the most difficult task is to provide reliable data to investigate the model of exhaust emissions, particularly since the official transport-related statistics are characterized by high generality and may for example focus on the vehicle number. The resultant values obtained from models are estimates, whose applicability range may be limited. Hence, the search for new methods of assessment of exhaust emissions from transport is desired and the assessment itself necessary. One of the fundamental parameters of inaccuracy is determining the exhaust emissions for a single vehicle. These emissions are most frequently assumed based on the exhaust emissions standards.
In relation to exhaust emissions research within the realm of analysis their two types may be distinguished (in terms of their goals). These are:

- exhaust emissions comparative research from passenger and heavy-duty vehicles or combustion engines. These can be investigations conducted directly on chassis or engine dynamometers using the equipment fitted on the test stand and using on-board measurement equipment. Such investigations allow an assessment of the gaseous exhaust emissions utilizing the on-board method. These can also be comparative investigations of exhaust emissions from vehicles fueled with different types of fuels including alternative fuels,
- investigations aiming at estimating the emission indexes by determining the exhaust emissions from different vehicle categories under actual traffic conditions utilizing the on-board method and comparing them to the admissible exhaust emissions values (Euro). The indexes allow an approximate assessment of the exhaust emissions from the discussed vehicles under actual traffic conditions.

The subject of further analysis will be the concept and development of a universal system for the measurement of exhaust emissions under actual operating conditions (using on-board measurement equipment) of any mode of transport equipped with combustion engines [21]. The presented results are the effect of 9 years of research under actual operating conditions performed on a group of over 200 vehicles.

Aside from measurements performed on motor vehicles (including off-road) the system allows coordinating the exhaust emissions measurements from heavy-duty trucks, buses (including hybrid), construction and farm machinery (non-road) [18], rail vehicles, ships and aircraft fitted with piston and jet engines:

– Gaseous exhaust emissions:

Semtech DS (Sensors; CO_2/ CO, THC/NMHC, NO_x),
Ecostar Gas (Sensors; CO_2/CO, THC/NMHC, NO_x, NH3),
M.O.V.E. Gas (AVL; CO_2, CO, THC, NO_x),

– Particle mass (PM) & number (PN) emissions:

Ecostar PM & PN (Sensors; ion mobility),
M.O.V.E. PM (AVL; gravimetric + photoacoustic),
Micro Soot Sensor (AVL; photoacoustic),
Particle Counter (AVL; counter TSI),
EEPS PN size distribution (TSI; electrical mobility).

Vehicles of the GVW of up to 3500 kg (mopeds, motorcycles, passenger vehicles and delivery trucks) are tested on a chassis dynamometer in standard homologation tests. The proposed concept and methodology is related to the assessment of the environmental performance of a vehicle under actual operating conditions. Passenger vehicles are subject to intermittent evaluation at inspection stations, however the testing conditions during the inspections provide a limited operating range for the engine, much narrower than in actual traffic. The engines operate when fitted in the vehicles and their evaluation may be performed on a chassis dynamometer or using the developed methodology of testing under actual operating conditions.

As for other applications of combustion engines in motor vehicles of the GVW exceeding 3500 kg (heavy-duty trucks and buses), off-road vehicles, construction and farm machinery (non-road), rail vehicles, ship and aircraft fitted with piston and jet engines – the engines are removed and tested on engine dynamometers. These engines operate under artificial conditions, usually much different than the actual ones. For the assessment of exhaust emissions after a certain period of operation the engine would have to be removed from the vehicle, which is technically and economically infeasible. The proposal to test vehicles using portable exhaust emissions measurement systems is a universal solution as it can be used in vehicles of all applications, where the same engines are applied.

The authors of the paper propose an introduction of an exhaust emissions conformity factors (*CF*) denoting the multiple of the increase or decrease of the exhaust emissions under actual traffic conditions compared to the homologation tests. Such an index has been defined for a given exhaust component:

$$CF_j = \frac{E_{real,j}}{E_{NEDC(ETC,WHTC),j}} \tag{1}$$

where:

j – exhaust component for which the conformity factor was determined,
$E_{real,j}$ – emission under actual traffic conditions [g/km],

$E_{NEDC,j}$ – emission measured in the NEDC test [g/km] or other tests such as ETC, WHTC (for heavy-duty vehicles).

The proposed exhaust emissions correction coefficient will adapt the homologation emission values obtained in the tests to the actual traffic conditions of a vehicle. Hence, the factors, referred to as *CF*, should be dimensionless and determined for different emission categories:

– passenger and light-duty trucks (up to 3500 kg) – for which the emission limits are prescribed in grams per kilometer [g/km],
– heavy-duty and non-road vehicles – for which the emission limits are prescribed in grams per kilowatt hour [g/kWh].

2.2 On-road passenger vehicle tests

The performed validating tests of the exhaust emissions from passenger vehicles fitted with Euro 3–Euro 5 (Figure 1) compliant gasoline and diesel engines under actual traffic conditions were the first application of the developed tool – a universal on-board exhaust emissions measurement equipment. Determination of the exhaust emissions under actual traffic conditions and comparing it with the values obtained on a chassis dynamometer in the homologation test allowed determining of the emission index that answers the question whether the on-road emission is comparable and to what extent it is comparable with the emission obtained during the homologation test. At the same time this is a validation of the driving conditions in the homologation test (developed many years ago) and the actual conditions of operation.

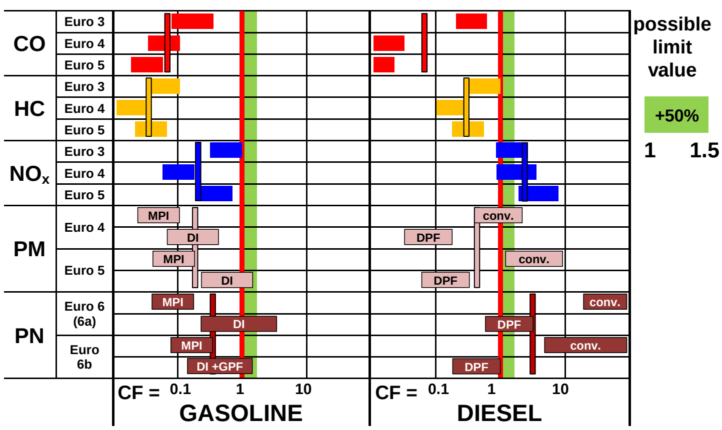


Figure 1: Exhaust emissions indexes for diesel- and gasoline-fueled passenger vehicles (9 years of research, vertical line denotes average values)

A high variability of the obtained results has been observed for different driving conditions: for carbon monoxide, the higher the emission category the lower the emissions (CF_{CO} = 0,02–0,2). We have the same dependence for hydrocarbons (CF_{HC} = 0,01–0,1). It is noteworthy that the emission of these two compounds is not greater under traffic conditions compared to the homologation conditions. This pertains to both gasoline and diesel engines. For nitrogen oxides, the conformity factor is lower than 1 (CF_{NOx} = 0,08–0,95) for gasoline-fueled vehicles and greater than 1 for diesel-fueled vehicles (CF_{NOx} = 1–5).

The greatest variation of the conformity factor was observed for particulate matter. When it comes to the mass of the particles, their values are very low for multipoint fuel injected engines (CF_{PM} = 0,02–0,2) while for direct injected engines these values are greater (CF_{PM} = 0,09–2). For diesel engines without particle filter, the conformity factor CF_{PM} assumes values from 0,3–10, and for engines fitted with the particle filter (irrespective of the emission category) the recorded values are several times lower (CF_{PM} = 0,02–0,2). When measuring particulate matter, the following values were obtained: for vehicles fitted with MPI gasoline engines the emission indexes CF_{PN} were 0,04–0,4, for direct injected gasoline engines these factors were higher (CF_{PN} = 0,2–5) and for vehicles fitted with the particle filter, factor CF_{PN} fell in the range 0,3–1,5. For diesel vehicles without particle filter the conformity factors were in the range of CF_{PN} = 3–100 and for vehicles fitted with particle filter, the values were several times lower (CF_{PN} = 0,2–5).
From the data analysis it is known that the emission values obtained under actual operation are exceeded for diesel vehicles (nitrogen oxides and particulate matter), while for gasoline engines the emission standard is exceeded only in particle number for direct injected engines.

2.3 On-road tests of heavy-duty trucks and buses

The emission level from city buses, due to the specificity of their use, can only be assessed during actual conditions of their operation. The most suitable tests for these buses are performed on the urban routes. Using a portable exhaust emission measurement system, the authors measured the emission level of a hybrid and a conventional bus in city traffic in the city of Poznan. The conditions were selected to enable the most accurate reflection of the actual traffic conditions: the traffic on the selected bus route reflected the average traffic on all Poznan city routes. The objects of the tests were conventional and hybrid buses manufactured by Solaris (Figure 2). The buses were selected for their similarities as well as to enable a comparison of their functionality and environmental performance under actual traffic conditions (the bus engines were Euro 5 compliant).

Engine type	Diesel conventional	Parallel hybrid	Serial hybrid
			
Made by	DAF PR265	Cummins ISB 6.7 250 B + Allison Ep50	Cummins ISB 6.7 285H + Vossloh Kiepe
Displacement	9.2 L (228 kW)	6.7 L (180 kW)	6.7 L (209 kW)
Torque/ Speed	1450 N·m 1100–1710 rpm	1008 N·m 1200 rpm	1008 N·m 1200 rpm
Emission category	Euro V–EEV SCR/DPF	Euro V–EEV SCR/DPF	Euro V–EEV SCR/DPF

Figure 2: Characteristics of the tested objects – city buses

By characterizing the conformity factors for heavy-duty vehicles, the following were obtained (averaged results for 48 heavy-duty vehicles and 73 buses):
1. For heavy-duty vehicles:

- The conformity factor of carbon monoxide CF_{CO} is in the range from 0,2 (for the emission category of Euro V), to 5 (for the emission category of Euro III and high vehicle mileage),
- The conformity factor of hydrocarbons CF_{HC} is in the range from 0,2 (for the emission category Euro III and low mileage) to 1,1 (for the emission category of Euro V),
- The conformity factor of nitrogen oxides CF_{NOx} is in the range from 0,2 (for vehicles of low power-to-capacity ratio, of the emission category of Euro III) to 5–6 (for rural conditions, for newest vehicles of high power-to-capacity ratio in which the aftertreatment system operates in insufficiently high temperature),
- The conformity factor of particulate matter CF_{PM} is in the range from 0,2 (for the emission category Euro III and low mileage) to 5 (for the emission category Euro IV for vehicles without particle filters).

2. For buses (Figure 3):

- The conformity factor of carbon monoxide for CNG buses is CF_{CO} = 0,2–4 (lower values were obtained for vehicles of the emission category of Euro V, and greater values for vehicles of the mileage in excess of 1 million kilometers and the emission category of Euro III); for buses fitted with diesel engines, the values of CF_{CO} are from 0,2 to 5 (for the emission category of Euro III–Euro IV) and for buses of the emission category of Euro V: CF_{CO} = 0,1–0,8 (including hybrid buses CF_{CO} = 0,1–0,5),
- The conformity factor of hydrocarbons reaches similar values to those of carbon monoxide: for CNG buses it is in the range CF_{HC} = 0,3–3 (lower values were obtained for vehicles of the emission category of Euro V, and greater values for vehicles of the mileage in excess of 1 million kilometers and the emission category of Euro III); for conventional buses fitted with diesel engines the values of CF_{HC} are from 0,1 to 1,2 (for the emission category of Euro III–Euro IV) and for the emission category of Euro V: CF_{HC} = 0,01–0,2 (including hybrid buses CF_{HC} = 0,01–0,08),
- The conformity factor of nitrogen oxides for CNG buses is CF_{NOx} = 0,2–1,5 (lower values were obtained for vehicles of the emission category of Euro V, and greater values for vehicles of the mileage in excess of 1 million kilometers and the emission category of Euro III); for conventional buses fitted with diesel engines the values of CF_{NOx} are from 0,8 to 3 (for the emission category of Euro III–Euro IV) and for the emission category of Euro V: CF_{NOx} = 0,8–2; the greatest emission indexes were recorded for hybrid vehicles CF_{NOx} = 2–5, which confirms a mismatch of the vehicle and the engine,
- The conformity factor of particulate matter for buses fitted with diesel engines reaches values of CF_{PM} = 1–4,2 (for the emission category of Euro III–Euro IV not fitted with a particle filter) and for the emission category of Euro V: CF_{PM} = 0,3–0,8, among which hybrid vehicles were also classified whose PM conformity factor was 0.3–0.9).

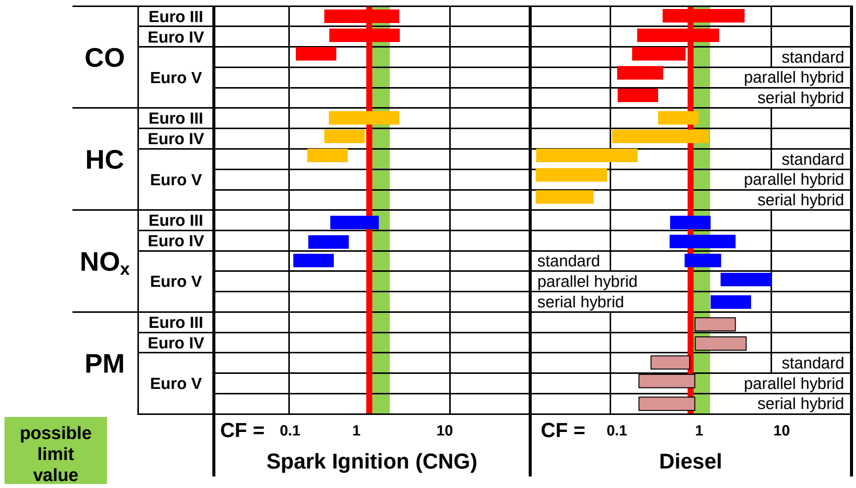


Figure 3: Exhaust emission indexes for city buses under actual conditions of operation

3 Selected aspects of sustainable transport system model

3.1 Assumptions

A model of a proecological transport system (**MEST**) must have properties allowing for studies on the modal interaction with regard to the level of emissions of harmful compounds. Regarding to this information, it has been defined taking into account the following basic elements [14], [15], [16] (description of symbols in point 3.2):

$$\mathrm{MEST} = \langle \mathrm{ST}, \mathrm{GE}, \mathrm{FE}, \mathrm{QE}, \mathrm{OE}, \mathrm{IE} \rangle \tag{2}$$

where:

– **ST -** set of types of vehicles used to perform transport tasks, described as records of a database **BST**,

– **GE -** structure of transport network showing in form of links (***LE***) between origin, intermediate, and destination points (***WE***) for passenger and cargo streams,

– **FE -** characteristics of the network elements representing actual properties of vehicles (**FSP**) and transport connections (characteristics connected with existing databases, especially characteristics assigned to nodes of the network (**FEW**), and characteristics assigned to edges (**FLE**) of a network resulting from the movement of vehicles),

– **QE -** volume of transport tasks identified at the input to the system (demand for transport services reported by the clients),

– **OE -** organization understand as a way to carry traffic flow through the transport network from point of origin to point of destination with regard to the emission levels, transport fleet, infrastructure and economic conditions,

– **IE -** databases and information systems.

Model of Environmentally Friendly Transport System (MEST) should take into account:

– passenger and freight movements,
– external costs of transport
– the emission of harmful compounds of exhaust gases, including GHG,

– coefficient k which allow to calculate emissions by means of transport in real traffic conditions,

– dependencies between the parameters of the transport network, the size of the traffic volume and emission of harmful compounds.

As input data used for the model of designing of the proecological transport system (EMITRANSYS) authors used the results of measurements of exhaust emissions obtained with portable emission analyzers (PEMS). The analyzers measure the concentration of gaseous exhaust components and particulate matter (mass and number) and are fitted with vehicle data acquisition systems (engine and vehicle parameters). In the tests performed under actual operating conditions the authors' proprietary research methodology was applied.

3.2 Parameters and decision variables of the model

Individual components of the model have been described in detail in [14]. Each *st* vehicle type was characterized by a vector of technical and technological, environmental and economic parameters in the form:

$$\mathbf{v}(\mathbf{st}) = [rsp(st), neu(st), q(st), m(st), c(st), em(s,st)] \tag{3}$$

where:

rsp(*st*) –type of engine of the *st* vehicle,
neu(*st*) –type of EURO standard of the *st* vehicle,
q(*st*) –load/capacity of the *st* vehicle,
m(*st*) –type of transport (passenger, cargo) of the *st* vehicle,
c(*st*) –unit cost of transport of the *st* vehicle,
em(*s,st*) –unit emissions of *s*-th exhaust component for the *st* vehicle.

Database of transport vehicles (**BST)** was written as a three elements vector, **BST=[S, ST, v(st)].** The structure of the transport system in the model (**MEST)** was presented using a graph **GE**, **GE** = ⟨***WE***, ***LE***⟩, where the set ***WE*** is a set of transport nodes numbers, which in the real transport network are points of origin and destination of passengers and cargo flow and cargo handling or passengers intermediate points (for example transhipment points, logistics centers, intermodal transport terminals etc.), while ***LE*** is a set of real transport connections.

Database characteristics of the transport vehicles and structural elements of the transport system (**BFE)** was written as a vector: **BFE=[FLE, FEW, FSP],** where **FLE** is a database connected with connections, **FEW** – a database connected with nodes and **FSP** is a database connected with transport vehicles. A set of characteristics of elements comes from specifications of individual vehicles (i.e .emission standards *nes*(*n*(*st*), *st*) and average unit cost of operation dependent on travel distance), individual nodal system components where it is possible to service, generate or take away freight and passenger flow, as well as technical parameters of transport links, such as length *d*(*I*, *i'*), section speed limits *v*(*I*, *i'*), flow capacities *q*(*I*, *i'*) and other technical parameters [8].

The volume of transport tasks in the EMITRANSYS model was presented as a two-elements vector ***QE***, ***QE*** = [**X1**, **X2**], where **X1** is a matrix of demand for freight transport, and **X2** is a matrix of demand for passenger transport. The individual matrices were composed on matrices containing information about the demand for transport. Demand

segments are characterized by material, technical and economic determinants of satisfying the needs of transport (eg. transport of mining products or furniture, transport of passengers traveling to and from work or transport of passengers traveling on business trips) [8].
The influence of the engine type, the Euro standard and the length of traveled p-th distance in relation (a, b) on the emission is described by coefficients $\psi(s,st,neu(st),rsp(st),p,a,b)$. After projection, they take a form of $\psi a(s, st, p, a, b)$.
Important part of the model are databases and information systems **IE**. In the EMITRANSYS model used data from the following sources:

- National Logistic System (in the Figure 4 – KSL),
- Road Infrastructure Manager (in the Figure 4 – GDDKiA),
- Ministry of Infrastructure & Development (in the Figure 4 – MIiR),
- Railway Infrastructure Manager (in the Figure 4 – PKP PLK),
- Civil Aviation Authority (in the Figure 4 – ULC),
- National Water Management Authority (in the Figure 4 – KZGW),
- Central Registry of Vehicles and Drivers (in the Figure 4 – CEPiK),
- Central Statistical Office of Poland (in the Figure 4 – GUS),
- Eurostat.

3.3 Selected model limitation and evaluation criteria

Among the criteria of evaluation of a transport system in terms of the environment one should distinguish the excess of admissible standards and impact of transport on human and natural environment. Taking into account above, indicators of solution quality assessment have been formulated related to the excess of admissible emission of individual exhaust components and noise.
In the case of shaping proecological transport system we could mention the following indicators:

- indicators concerning to the structure of transport,
- indicators for the evaluation of transport infrastructure in the aspect of proecological.

To the first group of indicators we can include the participation rate of proecological transport work in relation to the total transport work $\alpha^{PT}(r)$ presented by the formula:

$$\forall k \in \boldsymbol{K} \ \alpha^{PT}(r) = \frac{q(1,k)}{\sum_{r \in \boldsymbol{R}} q(r,k)} \cdot 100\% \tag{4}$$

where:
r – mode of transport,
k – the type of transport,
$\alpha^{PT}(r)$ – the share of transport work mode of transport no. r in total transport work,
$q(r, k)$ – the volume of transport work mode of transport no. r in types of carriage no. k.

This indicator determines the share of transport work done by the transport which is environmentally friendly (mostly by railways) in transport work carried out by all modes of transport. On the basis of this indicator we will assess involvement of rail transport in the implementation of transport tasks in the transport system.

On selected areas in Poland have been identified exceeding the permissible concentrations of the compounds emissions [1]. The developed solution should also be evaluated in terms of exceeding the acceptable level of emissions. So to the second group of indicators we can include the indicator to assess crossing of the limit value of compounds for the vehicle $\kappa(st, s, ob)$:

$$\forall ob \in \boldsymbol{OB} \quad \forall st \in \boldsymbol{ST} \quad \forall s \in \boldsymbol{S} \quad \forall rsp \in \boldsymbol{RSP} \quad \forall neu \in \boldsymbol{NEU}$$

$$\kappa(st, s, ob) = \frac{em(s,st,neu,rsp)}{NEU(s,ob)} \cdot 100\% \tag{5}$$

where:
ob – given area,
em(*s*,*st*,*neu*,*rsp*) – emissions of no. *s* emitted by vehicle type no. *st* with Euro class no. *neu* and type of engine no. *rsp*,
NEU(*s*,*ob*) – standard limit values of harmful compounds in a given area.

Feasible solutions must keep the following constrains:
- entire transport demand must be satisfied,
- material and passenger flows (additivity of traffic flow) must be sustained,
- used to perform the tasks of transport only the number of vehicles that is available,
- the number of disposed vehicles cannot be exceeded,
- capacity of transport links (sections) cannot be exceeded,
- ability of selected means of transport to move on individual sections of network,
- area/section access restrictions according to pollution,
- acceptable levels of exhaust emission of individual exhaust components cannot be exceeded,
- loading capacity and defined number of passengers per vehicle,
- vertical and horizontal gauge is not overpassed,
- maximum density of traffic on individual sections of network,
- total mass of the vehicle shall not exceed the permissible total weight applicable on a particular link,
- axle load of a vehicle shall not exceed the permissible load on a particular link.

3.4 Decision aiding model in the scope of pro-ecological creation of transport systems

Model of Environmentally Friendly Transport System (MEST) was prepared using classic four step transport model [23]. In this approach we need network model, where there are communication areas, nodes, stops of public transport as well as sections and lines in public transport with appropriate timetables. Based on socio-demographic structure of users and spatial management of area in the first step (trip generation) there are determine the volume of the flow generated in points of origin and absorbed in points of destination, based on surveys, demographic data and the explanatory variables. In the next step (trip distribution) there are determine based on eg. gravity model the volume of the traffic flow between points of origin and destination. In the third step (modal split) there are determine based on surveys

what part of the transport will be carried out using concrete transport mode. In the last step (route assignment) based on surveys and experience there is a selection of routes between origins and destinations in transportation networks. On the end we achieved Model of Environmentally Friendly Transport System (MEST).
The **MEST** model has been implemented in the PTV VISUM software. This is a tool that enables performance of multivariant analyses of traffic organization in a transport network in terms of minimization of exhaust emissions. PTV VISUM is also a tool to design, analyze and model transport systems. The development of the model implementation allows for an effective decision aiding in the scope of the implemented solutions, assessments of planned investments (e.g. road construction), their impact on the surrounding environment etc. The diagram of exhaust emissions modeling and the investigations of the exhaust emissions in the network surroundings have been presented in Figure 4.
Using MEST (Model of Environmentally Friendly Transport System) it is possible to conduct analysis on three scale:

– macro scale - e.g. for country or bigger area,
– meso scale - e.g. for voivodship or transport corridor,
– micro scale - eg. for one line or road.

4 Example of the application of research – Case study of sustainable development of the transport system with the EMITRANSYS model

The problem is the determination of the exhaust emissions under traffic conditions depending on the terrain conditions and comparing it with the standard values. The research object was a sport utility vehicle fitted with automatic transmission and a 3.6 dm^3 206 kW gasoline engine; the vehicle complied with the Euro 5 standard.

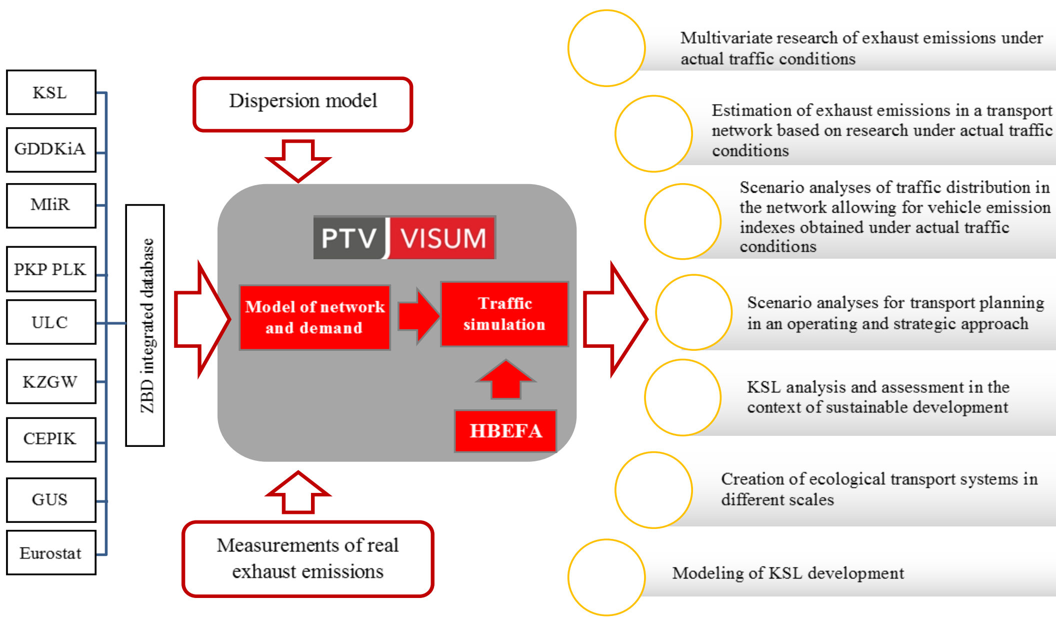
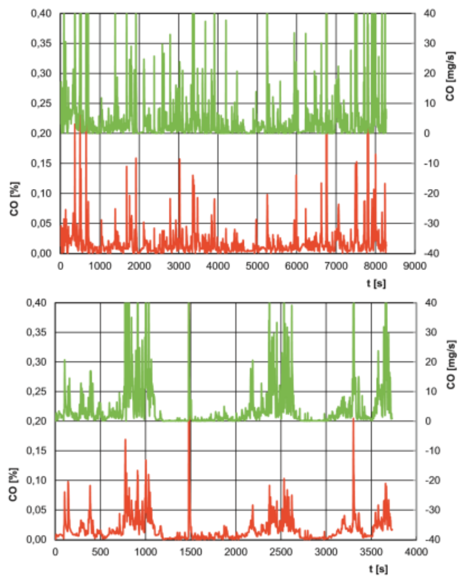


Figure 4: Modeling of exhaust emissions using VISUM [14], [15]

Using the portable exhaust emissions measurement system (PEMS) the concentration of the emission of carbon monoxide, hydrocarbons, nitrogen oxides, carbon dioxide and particulate matter (mass and number) was determined. The concentration of carbon monoxide on the flat road portion was approx. 0.02% (in most of this road portion below this value, hence not exceeding 200 ppm). Singular dynamic engine operating conditions resulted in an abrupt increase of the concentration, which led to the emission of CO reaching 40 mg/s (Figure 5a). The concentration of carbon monoxide in the mountainous area was mostly below 0.01% (in most of this road portion below this value hence not exceeding 100 ppm). Changes in the engine operating conditions resulted in an abrupt increase of this concentration, which led to the emission of CO exceeding 40 mg/s (Figure 5b).
The concentration of hydrocarbons during the tests did not exceed 10–15 ppm in flat terrain and 30 ppm in the mountainous area. Singular road conditions required a sudden increase in the fuel dosage, which resulted in an increased hydrocarbon concentration. The values of the emission rate of the discussed component, except the initial and final part of the test, did not exceed 2 mg/s in flat terrain (Figure 6a) and 4–5 mg/s (Figure 6b) in the mountainous area.

a)
b)


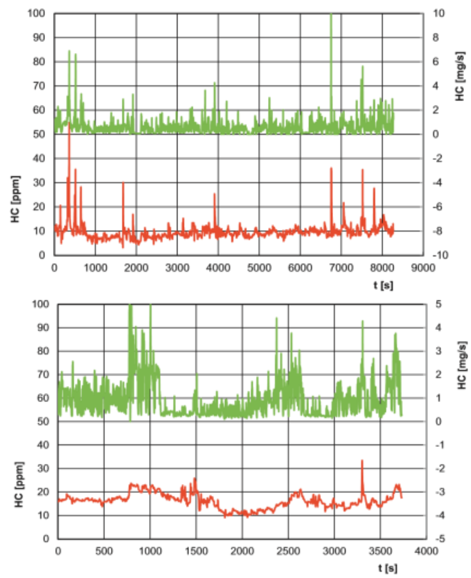
a)
b)


Figure 5: Concentration and emission rate of carbon monoxide when driving in: a) flat terrain, b) mountainous area

Figure 6: Concentration and emission rate of hydrocarbons when driving in: a) flat terrain, b) mountainous area

Also, the concentration of the third exhaust component – nitrogen oxides– in the entire test in flat terrain maintained a very low level. The low values of this component obtained in the test were a result of a properly functioning three-way catalytic converter. The emission rate of nitrogen oxides in the entire test was minimum and did not exceed 1–2 mg/s. Any deviations from this value were caused by typical engine operation and no incidents were observed, in which these values would significantly exceed the recorded values (Figure 7a). In the mountainous area the concentration of nitrogen oxides was on the level of approx. 40 ppm. The emission rate of nitrogen oxides in the entire test was minimum and did not exceed 0.1–0.5 mg/s (Figure 7b). The nature of the changes in the emission rates of particulate matter has been shown in Figure 8. In the mountainous area in the initial phase, the value of the PM concentration oscillated around 0.15 mg/m^3 with a growing trend. Another phase was the time when the PM concentration abruptly decreased and maintained this minimum level. The last phase of the measurement was characterized by a significant growth of the PM concentration and despite certain oscillations it can be determined as the time of highest concentration. The nature of the changes in the emission rates of PM was in line with the changes of its concentration only slightly exceeding the value of 0.1 mg/s (Figure 8b).

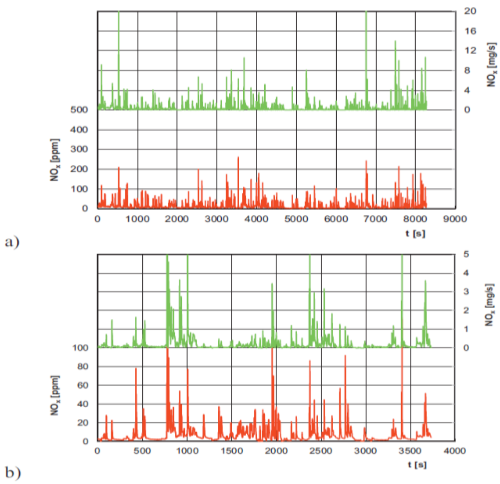


Figure 7: Concentration and emission rate of nitrogen oxides when driving in: a) flat terrain, b) mountainous area

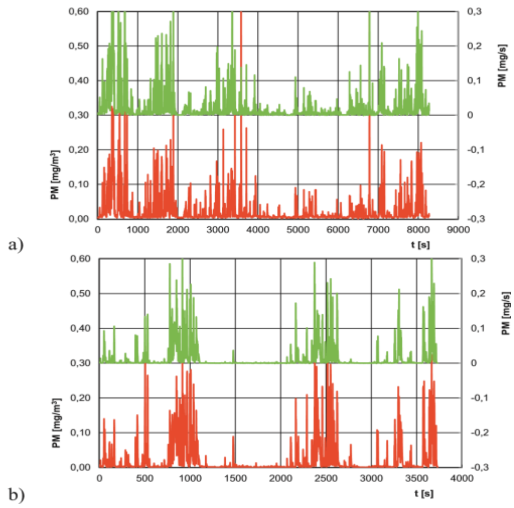


Figure 8: Mass Concentration and emission rate of particulate matter when driving in: a) flat terrain, b) mountainous area

The obtained results of the measurements were used for the performance of a simulation of a multivariate distribution of flow of cargo throughout the transport network in Poland according to three criteria: the criterion of minimization of carriage time (MC), criterion of minimization of carriage distance (MD) and criterion of costs of the exhaust emissions. The transport tasks covered the demand for passenger transport in private road transport (passenger vehicles), public road transport (buses) and public railway transport. Additionally, transport needs resulting from the carriage of goods in road and railway transport were taken into account. Each of the groups of road vehicles (passenger and heavy-duty) was divided into vehicles of a given emission category, engine displacement, type of fuel etc. This enabled the estimation of the extent of emissions of individual exhaust components in the transport system after the distribution of the traffic stream.

Using above data we conducted research on the network of Poland. We analyse the distribution of traffic flow on the transport network in two scales: macro scale – for the area of Poland and in meso scale – for transport corridor Warsaw – Lodz, wherte it is possible to use means of private transport (cars) and public transport (buses and trains). We took into account emission of two substances: carbon dioxide (CO_2) and nitrogen oxides (NO_x). The results of the conducted investigations have been presented graphically in Figures 9–13.

Figure 9 presents the network load of the flow of passengers in public and private transport and the flow of freight carried in road and railway transport.

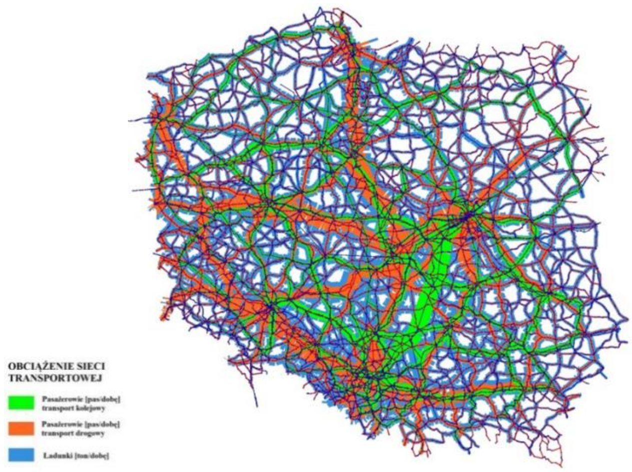


Figure 9: Transport network load with traffic flow units

In the next figures 10–13 generated exhaust emissions (CO_2 and NO_x) by following the realization of the transport demand in a transport system have been shown.

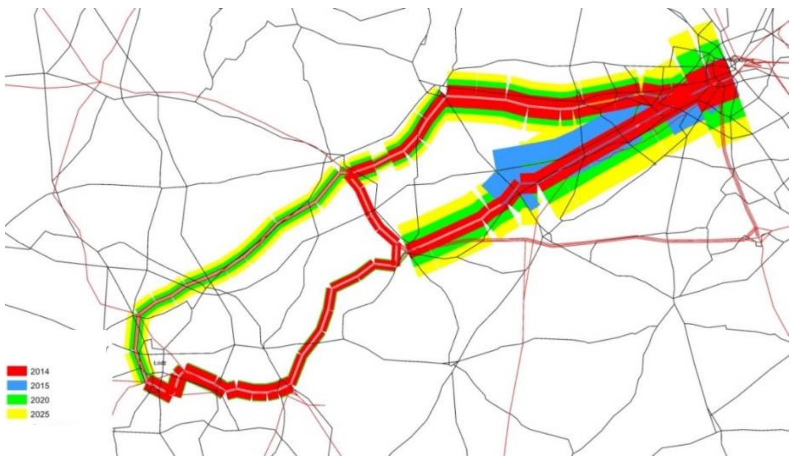


Figure 10: Volume of carbon dioxide (CO_2) emission for analyzed corridor (meso scale)

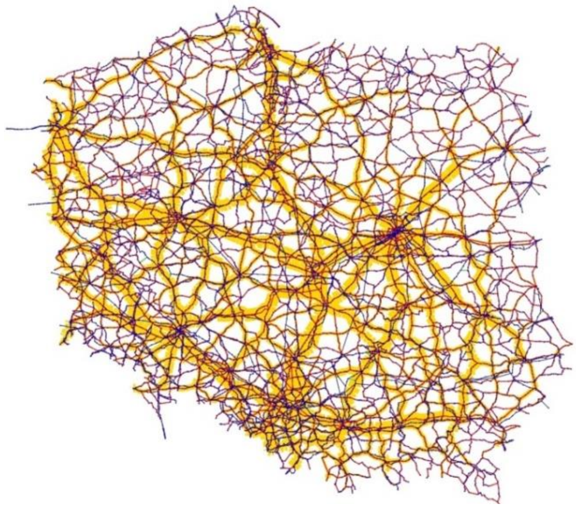


Figure 11: Volume of carbon dioxide (CO_2) emission for area of Poland (macro scale)

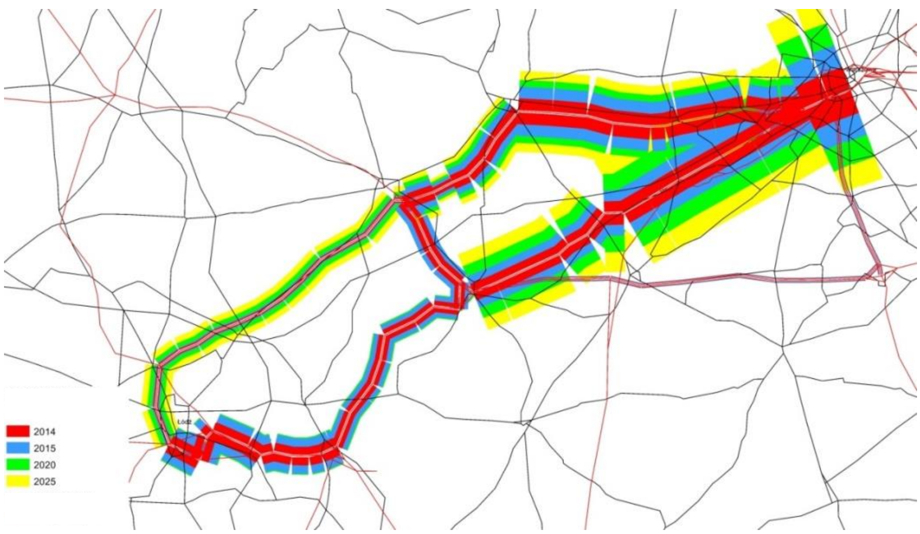


Figure 12: Volume of nitrogen oxides (NO_x) emission for analyzed corridor (meso scale)

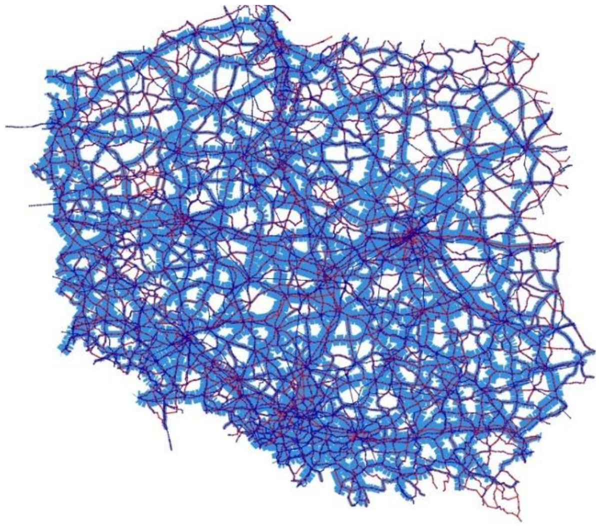


Figure 13: Volume of nitrogen oxides (NO_x) emission for area of Poland (macro scale)

5 Conclusion

The differences in the practical approach to the determination of engine or entire vehicle operating parameters in order to ascertain their emission level required a development of an individual methodology. This is primarily caused by the change of the approach towards emission testing from simulation tests under artificial conditions in laboratories to tests under actual traffic conditions.

As input data used for the model of designing of the proecological transport system (EMITRANSYS) authors used the results of measurements of exhaust emissions obtained with portable emission analyzers (PEMS). The analyzers measure the concentration of gaseous exhaust components and particulate matter (mass and number) and are fitted with vehicle data acquisition systems (engine and vehicle parameters). In the tests performed under actual operating conditions the authors' proprietary research methodology was applied. Based on the obtained results it has been confirmed that the emission of NO_x and particulate matter is a problem for diesel engines, but for vehicles fitted with gasoline engines the problem is the emission of particulate matter.

When designing such a system, we have to take into consideration the economic, ecological and social aspects. According to economic criteria transport system should be developed to provide the maximum efficiency at given costs or to obtain a given efficiency at the lowest possible cost. The efficiency can be achieved by, *inter alia*, appropriate traffic management or the use of intelligent transport systems. On the other hand developing transport systems is very important in the reduction of their negative impact on the environment (exhaust emissions or noise level).

A reduction in the exhaust emissions may be achieved by increasing the smoothness of the traffic flow and a reduction of the number of motor vehicles in city centers, integration with other modes of transport within the Park&Ride, Park&Go systems or increasing road transport quality and availability of public transit. The social functioning of transport systems may be realized through a developed network of public transit or a properly developed road infrastructure.

Developing sustainable transport systems is making the transport system most useful for the society by reacting to the transport needs that will guarantee access to all destinations. Developing transport systems also means determining the relationship between forecasted transport tasks, the transport equipment and the cost of task fulfillment by the system. In this regard, the analysis of the development of transport system infrastructure needs solving issues corresponding to successive stages of the investment. Firstly, we can talk about allocating resources, and secondly, about how to perform the tasks directed from the environment to the system.

ACKNOWLEDGEMENTS: The research has been financed by the National Centre for Research and Development – research project within the Applied Research Program (contract No. PBS1/A6/2/2012).

References

[1] Ambroziak T., Gołębiowski P., Pyza D., Jacyna-Gołda I., Merkisz-Guranowska A., Identification and analysis of parameters for the areas of the highest harmful exhaust emissions in the model EMITRANSYS, *Journal of KONES Powertrain and Transport*, **20**(3), (2013), 9-20.

[2] Ambroziak T., Jacyna M., Gołębiowski P., Wasiak M., Żak J., Wpływ rozłożenia potoku ruchu w sieci transportowej na poziom emisji CO2 przez środki transportu, *Prace Naukowe Politechniki Warszawskiej. Transport*, **97**, (2013), 9-18.

[3] Ambroziak T., Jachimowski R., Pyza D., Szczepański E., Analysis of the traffic stream distribution in terms of identification of areas with the highest exhaust pollution, *The Archives of Transport*, **32**(4), (2014), 7-16.

[4] Bai S., Chiu Y.-C.E., Niemeier D.A., A comparative analysis of using trip-based versus link-based traffic data for regional mobile source emissions estimation, *Atmospheric Environment*, **41**, (2007), 7512-7523.

[5] Briant R., Seigneur C., Gadrat M., Bugajny C., Evaluation of roadway Gaussian plume models with large-scale measurement campaigns, *Geoscientific Model Development*, **6**(2), (2013), 445-456.

[6] Costabile F., Allegrini I., A new approach to link transport emissions and air quality: An intelligent transport system based on the control of traffic air pollution, *Environmental Modelling & Software*, **23**, (2008), 258-267.

[7] Hausberger S., Rodler J., Sturm P., Rexeis M., Emission factors for heavy-duty vehicles and validation by tunnel measurements, *Atmospheric Environment*, **37**, (2003), 5237–5245.

[8] Jachimowski R., Kłodawski M., Lewczuk K., Szczepański E., Wasiak M.,: Implementation of the model of proecological transport system, *Journal of KONES Powertrain and Transport*, **20**(4), (2013), 129-139.

[9] Jacyna-Gołda I., Gołębiowski P., Jachimowski R., Kłodawski M., Lewczuk K., Szczepański E., Sivets O., Merkisz-Guranowska A., Pielecha J., Traffic distribution into transport network for defined scenarios of transport system development in aspect of environmental protection. *Journal of KONES Powertrain and Transport*, **21**(4), (2014), 183-192.

[10] Jacyna-Gołda I., Lewczuk K., Szczepański E., Gołębiowski P., *Rozłożenie ruchu w sieci transportowej z zastosowaniem modelu EMITRANSYS w aspekcie planowania rozwoju systemu transportowego*, Oficyna Wydawnicza Politechniki Warszawskiej, Warszawa-Poznań, 2014.

[11] Jacyna-Gołda I., Żak J., Gołębiowski P., Models of traffic flow distribution for various scenarios of the development of proecological transport system, *The Archives of Transport*, **32**(4), (2014), 17-28.

[12] Jacyna M., Some apects of Multicriteria Evaluation of Traffic Flow Distribution in a Multimodal Transport Corridor, Taking into Account Logistics Base Service, *The Archives of Transport*, **10**(1-2), (1999), 43-66.

[13] Jacyna M., Merkisz J., Proecological approach to modelling traffic organization in national transport system, *The Archives of Transport*, **30**(2), (2014), 31-42.

[14] Jacyna M., Wasiak M., *Simulation model to support designing a sustainable national transport system*, Index Copernicus International, Warsaw, 2014.

[15] Jacyna M., Wasiak M., Lewczuk K., Kłodawski M., Simulation model of transport system of Poland as a tool for developing sustainable transport, *The Archives of Transport*, **31**(3), (2014), 23-35.

[16] Jacyna M., Żak J., Jacyna-Gołda I., Merkisz J., Merkisz-Guranowska A., Pielecha J.,: Selected Aspects of the Model of Proecological Transport System, *Journal of KONES Powertrain and Transport*, **20**(3), (2013), 193-202.

[17] Lewczuk K., Żak J., Pyza D., Jacyna-Gołda I., Vehicle routing in urban area – environmental and technological determinants, *WIT Transactions on The Built Environment*, **130**, (2013), 373-384.

[18] Lijewski P., Merkisz J., Fuć P., The analysis of the operating conditions of farm machinery engines in regard to exhaust emissions legislation, *Applied Engineering in Agriculture*, **29**(4), (2013), 445-452.

[19] Merkisz J., Jacyna M., Merkisz-Guranowska A., Pielecha J., Exhaust emissions from modes of transport under actual traffic conditions, *Energy Production and Management in the 21st Century, WIT Transactions on Ecology and the Environment*, **190**, (2014), 1139-1145.

[20] Merkisz J., Merkisz-Guranowska A., Pielecha J., Nowak M., Jacyna M., Lewczuk K., Żak J., Exhaust emission measurements in the development of sustainable road transport. *Journal of KONES Powertrain and Transport*, **20**(4), (2013), 277-284.

[21] Merkisz J., Pielecha I., Pielecha J., Szukalski M, Gaseous and PM emission from combat vehicle engines during start and warm-up, *SAE Technical Paper 2010-01-2283*, (2010), 1-11.

[22] Merkisz-Guranowska A., Merkisz, J., Kozak M., Jacyna M., Development of a sustainable road transport system. *WIT Transactions on The Built Environment*, **130**, (2013), 507- 517.

[23] Ortuzar J, Willumsen L., *Modelling transport*, *4th Edition*, John Wiley & Sons, Ltd, Chichester, 2011.

[24] Russo F., Musolino G., A unifying modelling framework to simulate the Spatial Economic Transport Interaction process at urban and national scales. *Journal of Transport Geography*, **24**, (2012), 189-197.

[25] Vienneau D., De Hoogh K., Briggs D., A GIS-based method for modelling air pollution exposures across Europe. *Science of the Total Environment*, **408**, (2009), 255-266.

[26] Żak J., Gołębiowski P., Comparative analysis of the rail and road transport in the CO2 emission, *Combustion Engines*, **3**, (2015), 944-951.