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SELECTED ASPECTS OF THE MODEL OF PROECOLOGICAL TRANSPORT SYSTEM

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Abstract

The paper presents selected aspects of a design of a proecological transport system. The necessity of designing proecological transport systems results from forecasts of transport demand and adaptation of the infrastructure to the standards and requirements of the EU. The European Commission pays special attention to the need for sustainable and environmentally friendly transport. Warsaw University of Technology in collaboration with Poznan University of Technology performs a research work concerning the development of an environmentally friendly transport system - Project EMITRANSYS. One of its stages is a development of a mathematical model taking into account the minimization of both the negative impact of transport on the environment and the transportation costs. The paper proposes a general formulation of the mathematical model of a proecological transport system (MEST) including the boundary conditions. A function of criterion minimizes the emission of harmful exhaust components resulting from traffic distribution in a network. The point elements of the infrastructure in a model represent places where the infrastructure parameters change, i.e. crossroads, narrowed roads or reduced speed areas. In addition, the structure of the vehicle fleet embraces the characteristics of the emission levels of different types of exhaust components.

Keywords: *transportation, traffic modelling, proecological transport systems, exhaust emissions*

1. Introduction

One of the main factors spurring the development of techniques and technology in all fields of the industry is the necessity to reduce its negative impact on the environment. Road transport has the largest share in the total exhaust emissions into the environment of all its modes. The awareness of the increasing emissions from transport activities and related health risks is growing in Poland. Despite the crisis, passenger and freight transport grow continuously and an increased volume of transport in both the freight and the passenger segments thus nullifies the effects of actions taken in order to reduce the negative effects of transport. The continuing predominance of road transport obstructs achieving the desired effects of the proecological actions.

The negative impact of transport on the environment expresses itself through [17]:
- emission of greenhouse gases contributing to the climate change,
- local air pollution negatively influencing health and local natural environment,
- occupation of valuable natural zones and trenching their continuity (fragmentation) by new technical infrastructure contributing to the loss of biodiversity,
- noise that threatens human health and comfort.

Air pollution from transport depends on many factors [6, 13]. These include fuel composition, type and basic characteristics of the vehicles, infrastructure arrangement, speed and congestion. The following measures of pollution (especially air) can be distinguished: emissions and concentrations of primary pollutants (nitrogen oxides (NO_x), carbon monoxide – CO, sulphur dioxide – SO_2, lead – Pb, particulate matter – PM_{10}, $PM_{2.5}$ as well as dust and soot). These pollutants have a negative impact on materials and buildings, crops and forests and are harmful to human health and life.

The exhaust emission of harmful substances to the environment from motor vehicles is connected with the composition of fuel and its properties, as is in the case of sulphur compounds, cyclic hydrocarbons and heavy metals. The global warming effect forces the necessity of reducing the carbon dioxide emission [13]. Carbon dioxide is one of the most important causes of the greenhouse effect correlated to a development of the automotive industry and transportation. The next thing is the depleting resources of fossil fuels. These aspects generate large environment protection costs.

The analysis carried out by European Environment Agency [19] present the average cost of pollution in relation to 66 classes of vehicles with estimated costs caused by each of the classes on three types of roads (suburban, intercity and highways) in 30 countries and 108 cities. The estimated cost per kilometer, depending on the vehicle type and its surroundings, practically amounts from 0 to more than 30 eurocents for havey duty vehicles of more than 20 years of age not classified to any EURO standard.

Designing proecological transport systems is consistent with the recommendations of the EU Commission. The European Commission pays special attention to the need for sustainable and environmentally friendly transport. Therefore, it is necessary to search for methods and tools allowing the development of the transport system that minimize the negative impact of transport on the environment. To meet these needs Department of Logistics and Transport Systems at Faculty of Transport (Warsaw University of Technology) and Institute of Combustion Engines and Transport at Faculty of Machines and Transportation (Poznan University of Technology) initiated the EMITRASYS project to research and develop a model of a proecologcal transport system along with the guidelines for its development.

2. General assumptions for the development of the Model of the Proecological Transport System (MEST)

Analysing or assessing phenomena, processes or systems needs a precise point of view [12]. For the proecological transport system the assessment can be based on indicators such as: the emission level, the external costs or the quality of services. The main goal of the research carried out under the project of EMITRASYS is to obtain a tool for a multi-variant analysis to design a proecological transport system. Basically, it comes down to the rational apportionment of the traffic in the transport network minimizing the negative environmental effects of transport (the total social costs of transport).

Starting from the definition of a system, it can be stated that the proecological transport system is a set of elements interrelated organizationally in a way ensuring an effective realization of the movement of passengers and goods in a transport network with regard to the minimization of the total social costs of transport.

It was assumed that [11]:

a) Proecological Transport System (**EST**) aims at performing specified transport tasks in passenger and cargo segments with particular emphasis on minimizing the emissions of harmful exhaust gas components from road transport,
b) **EST** covers the whole economy and, geographically, the whole country,
c) **EST** supports other areas of economy (mining, manufacturing, distribution etc.) and realizes transport tasks arising from passenger and cargo transportation needs.

The basic elements of the system are:

– starting points for the transportation (origin points),
– points where the characteristics of the roads change (e.g. large nodal intersections, places where the number of lanes changes) and where the modes of transport change; these points (along with the associated loading infrastructure) are referred to as intermediate points,
– points where movement is finished (destination points),
– transport connections between these points,
– modes of transport that are restricted by infrastructure parameters (size, load capacity, speed patterns), economic parameters (unit costs) and the characteristics of the exhaust emissions,
– organization of information networks.

It is assumed that for freight transport all the transition points, logistics centres, intermodal terminals and other places of that type can constitute sources and mouths of material flows. For passenger transport it can be public transport stops, bus and train stations, airports, shopping malls and other similar places. Therefore, all traffic is created in those objects and aims at those objects. Thus, the demand for material of any type can be met from any node in a transport network offering this material. For this reason, the same transport relation will be serviced through different transport routes and, thus, by different modes of transport.

The movement of goods and passengers in the national transport system is realized by different modes of transport. The increase of the national transport system efficiency, whilst minimizing the harmful exhaust emissions, can be achieved mainly through rational use of the transport infrastructure. The parameters of the transport infrastructure as well as its location, density in the geographical areas, technical condition and maintenance have impact on the possibility of moving materials and passengers, the cost, the quality, the servicing time, etc.

3. Proecological Transport System Model (MEST)

3.1. General assumptions

The model of a system is a tool for the analysis and evaluation of the functioning of an existing or a designed system. A model should represent those properties of a real system that are relevant for the purposes of research [12]. Considering the nature and the tasks realized by a transport system, it is necessary to include the following properties:

– the structure of **MEST** representing the actual links between the elements of the transport system,
– the characteristic of the structural elements of **MEST** depicting the technical, economic or organizational properties of the system elements, relevant for the minimization of the exhaust emissions,
– the **MEST** transportation tasks specifying the system workload by material and passenger streams in the origin-destination relations,
– the **MEST** organization patterns of adapting the elements of infrastructure and equipment to the performed tasks.

Formally, the model of a proecological transport system (**MEST**) can be formulated as follows:

$$\mathbf{MEST} = \langle \boldsymbol{GE}, \boldsymbol{FE}, \boldsymbol{QE}, \boldsymbol{OE}, \boldsymbol{IE} \rangle, \tag{1}$$

where:

MEST – model of proecological transport system,
GE – structure of proecological transport system,
FE – set of characteristics of the structural elements of the proecological transport system,
QE – transportation tasks performed by **EST**,
OE – organization – the way of realizing the transportation tasks by **EST**,
IE – databases and information systems.

The structure of **MEST** determines the relationship between the above-mentioned elements as well as the relationship with the surroundings.

3.2. System structure (MEST)

The line objects such as roads, rails, inland channels, or aviation links are the elements of the transport system defining the possible relations between the points of origin, intermediate, and destination points through which goods or passengers are moved. This establishes the structure of the transport system. Proper realization of material and passenger flows relies on the following types of infrastructure:

- linear: the existing transport links (e.g. railway, roads),
- point: spatially separated facilities for cargo handling or servicing passengers (e.g. transhipment points, logistics centres, intermodal transport terminals, railway stations, airports), together with necessary equipment,
- informatics: any means of communication, data exchange standards and safeguards,
- appropriate means of transport determined by infrastructure, task and economic parameters.

Formally, the structure of proecological transport system has been noted by a graph:

$$\boldsymbol{GE} = \langle \boldsymbol{WE}, \boldsymbol{LE} \rangle, \tag{2}$$

where:
WE – set of nodes representing origin and destination points together with intermediate nodes for goods and passenger streams, $\boldsymbol{WE} = \{1, \ldots, a, \ldots, i, \ldots, i', \ldots, b, \ldots, WE\}$,
LE – set of transport connections (various modes of transport) between distinguished transport nodes.

Set ***WE*** is decomposed into three subsets: set of sources of material and passenger flows ***N***, set of destinations of material and passenger flows ***O***, and set of intermediate nodes ***P***. Thus, ***WE***:

$$\boldsymbol{WE} = \boldsymbol{N} \cup \boldsymbol{P} \cup \boldsymbol{O}. \tag{3}$$

To simplify the calculations it was assumed that sets ***N***, ***P***, ***O*** are pair wise disjoint. The nodes belonging to ***N*** are marked with symbol *a*, while nodes belonging to ***O*** are marked with symbol *b*. It was assumed that each two individual elements of **MEST** can be connected by proper transport relation (a, b).

An important aspect of modelling is defining databases necessary for the implementation of the **MEST** in the PTV VISUM environment. It was assumed that a description of a transport infrastructure in the proecological transport system model is based on the systematics of transport system elements presented in work [11]. For each of these elements the economic, quality and technical parameters will be defined.

The technical properties of roads and their sections affect the possible congestion and then have impact on the emissions level. Thus, the possibility of minimizing the congestion by taking operational and strategic decisions about apportioning of material and passengers flows into transport network is extremely important in the aspect of designing proecological transport.

For each pair of nodes $(a, b) \in \boldsymbol{E}$, $a \in \boldsymbol{N}$, $b \in \boldsymbol{O}$ the transport relation can be set. For each relation, a set of potential transport paths $\boldsymbol{P}^{ab}$ is known. A single path in a given relation (a, b) will be numbered with index *p*, where in $p \in \boldsymbol{P}^{ab}$.

$$\forall (a, b) \in \boldsymbol{E} \qquad \exists\, p \in \boldsymbol{P}^{ab}. \tag{4}$$

Freight and passenger transport is carried out mainly by road (75%) and rail (17%), so the model for proecological transport system includes national and regional roads and the main rail lines. For the purpose of computer implementation the following elements are included into the model databases:

– transportation nodes located in the network (including cross-roads, road and rail stops and stations, loading points, terminals, points where infrastructure characteristics are changed),
– areas of special land use (determining their position in relation to transport network i.e. regions, counties, municipalities, cities, housing estates; all places where material and passenger streams appear and disappear),
– regions representing areas of particular importance in terms of environmental protection such as Natura 2000.

To enable a multi-variant multimodal interaction, the areas must be associated with the modelled transport network and the points where material and passenger flows appear and disappear must be indicated. Individual transport nodes in the transport network are complex functional structures in which relations determining the direction of movement of traffic units must be programmed.

3.3. Parameterization of the MEST elements

The individual roads/railway paths and their sections in the transport network model are described with appropriate characteristics such as: length, number of tracks or lanes, traffic direction, speed limits, class of railway or road category, restrictions of tonnage (capacity), the terrain characteristics in which the road is located (e.g., plain, mountains, environmentally protected areas, the presence of noise barriers, etc.), dominant wind directions and speeds.

The model of the proecological transport system is an expanded version of the Model of the Logistics System of Poland presented in [11]. In addition to the movement of goods it includes passenger transport and exhaust emissions. Then the necessary sets are defined:

– types of vehicles $\boldsymbol{ST} = \{st\!: st = 1, \ldots, ST\}$, e.g.: $st = 1$ mopeds and motorcycles, $st = 2$ –passenger cars, $st = 3$ – minibuses with 6 to 9 seats, $st = 4$ – buses with 10 to 15 seats, $st = 5$ – buses with 16 to 45 seats, etc.,
– types of harmful substances generated during operation $\boldsymbol{S} = \{s\!: s = 1, \ldots, S\}$, wherein: $s = 1$ – carbon monoxide CO, $s = 2$ – hydrocarbons HC, $s = 3$ – nitric monoxide NO, $s = 4$ – nitric dioxide NO_2, $s = 5$ – particulate matter PM, $s = 6$ – carbon dioxide CO_2,
– types of engines (according to type of fuel and characteristics) $\boldsymbol{RSP} = \{rsp\!: rsp = 1, 2, 3, 4\}$,
– EURO standards of emission $\boldsymbol{NEU} = \{neu\!: neu = 0, 1, 2, 3, 4, 5, 6\}$.

Sections of transport links (i, i') are described by the following vector of parameters: $\langle q_{ii'}^{max}, q(i, i'), d_{ii'}, neu(i, i'), v(i, i'), c_{i,i',st,rsp}, ob(i, i')\rangle$, where:

– $q_{ii'}^{max}$ – section throughput,
– $q(i, i')$ – tonnage limitation on a section (i, i'),
– $d_{ii'}$ – length of a section (i, i'),
– $neu(i, i')$ – EURO standards required on a section,
– $v(i, i')$ – the maximum speed on the section (i, i'),
– $c_{i,i',st,rsp}$ – the cost of travel on the section by an st-th type of a mode of transport,
– $ob(i, i')$ – network area to which the section (i, i') is attributed.

In addition, the model includes characteristics of the mode of transport such as:

– level of emission of an s-th harmful component of exhaust gases by an st-th type of vehicle with an sp-th type of engine in a gnr-th standard of emission per unit of distance travelled $em(s, st, neu, rsp)$,
– loading capacity of an st-th type vehicle $q(st)$,
– the number of available st-th type vehicles with sp-th type engines in a gnr-th EURO standard $lp^{max}(st, sp, nr, k)$.

Freight road transport is performed by trucks of a wide range of capacity, ranging from vans of the GVW not exceeding 3.5 tons to high-tonnage trucks with GVW up to 24 tons. Passenger rail transport is realized with passenger railcars with 54 to 88 seats of different length and class of compartments. The railcars are pulled by electric or diesel locomotives as well as electrical multiple units. The type of used freight cars depends on the form and vulnerability of the transported material and railway class. Freight cars identified in MEST can carry from 20 to 65 tons of cargo.

The model takes into account the type of engine and fuel used for vehicle propulsion, including internal combustion engines powered by: gasoline, diesel, liquefied propane-butane LPG, compressed natural gas CNG or hybrid engines. The proposed characteristics are prepared to be used to distribute traffic in the transport network and estimate the pollution emitted into the environment.

4. Criteria and evaluation indexes in the proecological transport system

The basic criterion for assessing the effectiveness of all available and proposed solutions must be the economic criterion. This calculation must be run comprehensively in terms of micro (client level) and macro (transport sector) conditions and must also widely engage economic, ecological, and social issues. The indexes for the assessment of the development of the proecological transport system were constructed using the methodological assumptions described in [1, 8, 9, 19].

It was assumed that one of the evaluation criteria of designing the proecological transport system would be a function of the level of harmful exhaust components emitted from transport realizing transport tasks on a selected area of the network. The aim is to achieve the minimum value of this function. This can be written as:

$$\forall s \in \boldsymbol{S},$$
$$\sum_{(a,b)\in \boldsymbol{E}} \sum_{p\in \boldsymbol{P}^{ab}} \sum_{(i,i')\in \boldsymbol{LE}^{p,ab}} \sum_{st\in \boldsymbol{ST}} \sum_{k\in \boldsymbol{K}} \sum_{rsp\in \boldsymbol{RSP}} \sum_{neu\in \boldsymbol{NEU}} x^{p}(st,rsp,neu,i,i',k)\, d_{i,i'}\, em(s,st,neu,rsp), \tag{5}$$
$$\lambda(s,i,i')\ \psi(neu,st,rsp,s,p) \to \min.$$

Another important economic criterion of assessment is the cost of transport that should me minimal. It can be written as:

$$\sum_{st\in \boldsymbol{ST}} \sum_{neu\in \boldsymbol{NEU}} \sum_{(i,i')\in \boldsymbol{LE}} \sum_{k\in \boldsymbol{K}} \sum_{rsp\in \boldsymbol{RSP}} x(st,rsp,neu,i,i',k)\, d_{i,i'}\, c_{i,i',st,rsp} \to \min. \tag{6}$$

In order to assess the development of the proecological transport system and implement the above functions the necessary indexes are proposed. One of them is index $\kappa(st, s, ob)$ determining the ratio of the emission of an s-th type harmful substance and the standard of this emission acceptable in a given area by vehicles with a neu-th EURO standard, and an rsp-th type of engine. Formally, this index can be written:

$$\forall ob \in \boldsymbol{OB}\ \ \forall st \in \boldsymbol{ST}\ \ \forall s \in \boldsymbol{S}\ \ \forall rsp \in \boldsymbol{RSP}\ \ \forall neu \in \boldsymbol{NEU},$$
$$\kappa(st,s,ob) = \frac{em(s,st,neu,rsp)}{NEU(s,ob)} \cdot 100\%, \tag{7}$$

where $NEU(s, ob)$ are the standard limits of the emission of an s-th type component in a given area.

Selected indexes and measures of evaluation for designing the proecological transport system are presented in Tab. 1.

5. The mathematical formulation of the problem

For the clarity of the considerations, it is assumed that each of the transport relations $(a, b) \in \boldsymbol{E}$, in the transport network of **MEST** is characterized by a specific demand for transport defined as $x(a, b, k)$. In the analysed model the demand is expressed in tons of goods $x(a, b, 1)$ and number of

Tab. 1. Selected indexes and measures of evaluation for designing the proecological transport system. Source: own research

<table>
<tr><th>No.</th><th>Index name</th><th>Signature</th><th>Unit</th><th>Comment</th></tr>
<tr><td colspan="5">Indexes on the transport structure</td></tr>
<tr><td>1.</td><td>The share of proecological transport in relation to the total transport volume</td><td>$\alpha^{PT}(r)$</td><td>%</td><td>Determines the share of the rail transport in total transport volume realized by all modes of transport</td></tr>
<tr><td colspan="5">

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

where:
r – mode of transport: $r = 1$ – rail, $r = 2$ – road,
$\alpha^{PT}(r)$ – the share of an r-th mode of transport in the total transport volume,
$q(r, k)$ – the volume of transport of an r-th mode and k-th type of movement.</td></tr>
<tr><td>2.</td><td>The share of proecological transport in relation to the total transport volume in a given area</td><td>$\alpha^{PT}(r, ob)$</td><td>%</td><td>Determines share of the rail transport in total transport volume realized by all modes of transport in a given area</td></tr>
<tr><td colspan="5">

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

where:
$\alpha^{PT}(r, ob)$ – the share of transport volume of an r-th mode of transport at an ob-th area in the total transport volume,
$q(r, k, ob)$ – the share of transport volume of an r-th mode of transport at an ob-th area, and k-th type of movement.</td></tr>
<tr><td>3.</td><td>The coefficient of capacity utilization of a vehicle of given class</td><td>$\mu 1(st)$</td><td>%</td><td>Coefficient determines the average fulfilment of a mode of transport</td></tr>
<tr><td colspan="5">

$$\forall st \in \boldsymbol{ST} \quad \beta^{IMOD}(st) = \frac{q(st)}{q^{st}\, l(st)} \cdot 100\%,$$

where:
$q(st)$ – volume of carriage performed by an st-th type of a mode of transport,
$l(st)$ – number of st-th type vehicles for the transportation.</td></tr>
<tr><td>4.</td><td>The number of vehicles with the EURO emission standard not less than neu’</td><td>$\lambda(neu)$</td><td>%</td><td>This index determines the ratio of the number of vehicles with increased proecological standards to the number of all vehicles</td></tr>
<tr><td colspan="5">

$$\forall neu' \in \boldsymbol{NEU} \quad \lambda(neu') = \frac{\sum_{nr \geq nr'} \sum_{st \in \boldsymbol{ST}} l(st,neu)}{\sum_{neu \in \boldsymbol{NEU}} \sum_{st \in \boldsymbol{ST}} l(st,neu)} \cdot 100\%,$$

where:
$l(st,nr)$ – number of st-th type vehicles of an nr-th EURO standard used for the transport.</td></tr>
</table>

passengers $x(a,b,2)$. The demand for transport is synonymous to transport task expressed in matrices whose layouts are shaped by the transport relations, i.e. **X1** = $[x(a,b,1)]$ and **X2** = $[x(a,b,2)]$.

In the environmental aspect, the number of vehicles moved with goods or passengers on an individual connection (i,i') is important. Thus, the decision variable $x(st,rsp,neu,i,i',k)$ constitutes the number of vehicles of an st-th type with an rsp-th type of engine, and a neu-th EURO standard engaged in realizing a transport task. The optimization task of the apportionment of material and passenger streams in the transport network in the **MEST** can be formulated as follows:

For the defined:
- sets: $\boldsymbol{WE}$, $\boldsymbol{LE}$, $\boldsymbol{LE}^{p,ab}$, $\boldsymbol{N}$, $\boldsymbol{O}$,$\boldsymbol{P}$,$\boldsymbol{E}$, $\boldsymbol{ST}$, $\boldsymbol{S}$, $\boldsymbol{RSP}$, $\boldsymbol{NEU}$, $\boldsymbol{K}$, **X1**, **X2**,
- $q_{ii'}^{max}$ – capacity of an (i, i')-th transport connection,
- $c_{i,i',st,rsp}$ – cost *of* moving of an *st*-th type of vehicle on an (i, i')-th transport connection,
- set of paths in relations $(a, b) \in \boldsymbol{E}$,
- $\lambda(s, i, i')$ – coefficient of emissions of an *s*-th type of harmful components dependent on the section $(i, i') \in \boldsymbol{LE}$,
- $em(s, st, neu, rsp)$ – level of emission of an *s*-th harmful component by an *st*-th type vehicle with an *rsp*-th type of engine complying with an *nr*-th EURO standard per unit of distance,
- $\psi(s, neu, st, rsp, p)$ – coefficient of emission level of an *s*-th harmful component dependent on the type of vehicle, the EURO standard, the type of engine, and the covered distance,
- $neu(i, i')$ – EURO standards acceptable on the section $(i, i') \in \boldsymbol{LE}$,
- $nr(st)$ – EURO standard attributed to an *st*-th type of a mode of transport,
- and other.

The matrix of the decision variables must be determined:
- $\mathbf{X} = [x(st, rsp, neu, i, i', k)]$ – the number of vehicles moved in the transport network,

while the constraints:
1. All the demand for transport services must be met:

$$\forall (a,b) \in \boldsymbol{E} \ \ \forall k \in \boldsymbol{K} \ \sum_{p \in \boldsymbol{P}^{a,b}} \sum_{st \in \boldsymbol{ST}} \sum_{neu \in \boldsymbol{NEU}} \sum_{rsp \in \boldsymbol{RSP}} x^p(st,rsp,neu,i,i',k)\ q(st) \geq x(a,b,k). \tag{8}$$

2. The capacities of the individual connections (sections of paths) cannot be exceeded:

$$\forall (i,i') \in \boldsymbol{LE} \ \sum_{st \in \boldsymbol{ST}} \sum_{neu \in \boldsymbol{NEU}} \sum_{rsp \in \boldsymbol{RSP}} \sum_{k \in \boldsymbol{K}} x(st,rsp,neu,i,i',k) \leq q_{i,i'}{}^{\max}. \tag{9}$$

3. Material and passenger flows conditions:
   a) volume of flows must have a positive value (NP):

$$\forall (i,i') \in \boldsymbol{LE},\ \forall neu \in \boldsymbol{NEU},\ \forall rsp \in \boldsymbol{RSP},\ \forall k \in \boldsymbol{K},\ \forall st \in \boldsymbol{ST}, \\ x(st,rsp,neu,i,i',k) \geq 0, \tag{10}$$

   b) addictiveness of flows (AP):

$$\forall (i,i') \in \boldsymbol{LE},\ \forall neu \in \boldsymbol{NEU},\ \forall rsp \in \boldsymbol{RSP},\ \forall k \in \boldsymbol{K},\ \forall st \in \boldsymbol{ST}, \\ \sum_{(a,b) \in \boldsymbol{E}} \sum_{p \in \boldsymbol{P}^{a,b}} x^p(st,rsp,neu,i,i',k) = x(st,rsp,neu,i,i',k), \tag{11}$$

   c) preservation of flows (ZP):

$$\forall i \in \boldsymbol{WE},\ \forall neu \in \boldsymbol{NEU},\ \forall rsp \in \boldsymbol{RSP},\ \forall k \in \boldsymbol{K},\ \forall st \in \boldsymbol{ST}, \\ \sum_{i' \in \Gamma_i^{-1}} x(st,rsp,neu,i,i',k) - \sum_{i'' \in \Gamma_i^{-1}} x(st,rsp,neu,i,i'',k) = \begin{cases} -x(st,rsp,neu,i,i',k) & \text{for} \quad i \in \boldsymbol{N}, \\ 0 & \text{for} \quad i \in \boldsymbol{P}, \\ x(st,rsp,neu,i,i',k) & \text{for} \quad i \in \boldsymbol{O}. \end{cases} \tag{12}$$

4. Limiting access to given areas due to the EURO standards:

$$\forall k \in K,\ \forall neu \in \boldsymbol{NEU},\ \forall rsp \in \boldsymbol{RSP},\ \forall st \in \boldsymbol{ST}, \\ x(st,rsp,neu,i,i',k) \leq \operatorname{sgn}\left(\frac{nr(st)}{nr(i,i')}\right) lp^{\max}(st,rsp,neu,k). \tag{13}$$

5. Tonnage limitation:

$$\forall k \in K,\ \forall neu \in \boldsymbol{NEU},\ \forall rsp \in \boldsymbol{RSP},\ \forall st \in \boldsymbol{ST},$$

$$x(st, rsp, neu, i, i', k) \leq \operatorname{sgn}\left(\frac{q(st)}{q(i,i')}\right) lp^{\max}(st, rsp, neu, k), \tag{15}$$

must be kept. The criteria function given by formula (2) or (3) is minimized.

5. Conclusions

The awareness of health risks connected to the emission of harmful components of exhaust gases caused by the advancement of the automotive industry is growing. Despite the efforts undertaken to reduce the emission through application of innovative technologies (catalytic converters, reduction of fuel consumption, hybrid engines) the exhaust emissions are still a significant problem.

Unfavourable branch structure of movements (the dominant share of road transport) and the continuous growth of passenger and freight transport obstruct the achievement of desired results. More than half of the travels in Europe are for distances up to 5 km, for which the amount of harmful emissions is greater.

Therefore, special attention should be devoted to increasing the share of low-emission vehicles in the national transport system. The basic criterion for assessing the effectiveness of all available and proposed solutions should be the economic calculation covering technological, economic, environmental, and social issues.

The modes of transport are integral elements of a transport system, hence the development of each of them has certain effects on the other modes. With the development of transport networks and the increasing intensity of traffic and average speeds, such factors affecting the environment as ecology, safety, and energy consumption must be emphasized.

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References

[1] *Air quality in Europe – 2012 report*, EEA Report No. 4/2012.

[2] Ambroziak, T., Żak, J., *Kryteria oceny rozłożenia strumienia ładunków w sieci logistycznej uwzględniając komodalność transportu*, Prace Naukowe Politechniki Warszawskiej. Transport, Nr 75, Warszawa 2010.

[3] Chiqueto, S., Mackett, R., *Modelling the Effects of Transport Policies on air Pollution,* The Science of the Total Environment, Vol. 169, pp. 265-271, 1995.

[4] Colovile, R. N., et. al., *The Transport Sector as a Source of Air Pollution*, Atmospheric Environment, Vol. 35, Iss. 9, pp. 1537-1565, 2001.

[5] Daganzo, C., *Logistics Systems Analysis*, Springer, Berlin-New York 1999.

[6] Danklefsen, N., *Obliczanie kosztów zewnętrznych w sektorze transportu*, Parlament Europejski, Bruksela 2009.

[7] Green Paper on *Towards Fair and Efficient Pricing in Transport*, European Commission, COM (95) 691 final Brussels 20.12.1995, Fair Payment for Infrastructure Use: A phased approach to a common transport infrastructure-charging framework in the EU. COM (1998) 466 final. Brussels. 27.07.1998.

[8] Gronowicz, J., *Ochrona środowiska w transporcie lądowym*, Wydawnictwo Instytutu Technologii i Eksploatacji, Poznań-Radom 2004.

[9] Inspekcja Ochrony Środowiska: *Ocena jakości powietrza w strefach w Polsce za rok 2011*, Warszawa 2012 (www.gios.gov.pl).
[10] Inspekcja Ochrony Środowiska: *Zanieczyszczenie powietrza w Polsce w 2009 roku na tle wielolecia*, Warszawa 2011 (www.powietrze.gios.gov.pl).
[11] Jacyna, M. (red.), *System logistyczny Polski. Uwarunkowania techniczno-technologiczne komodalności transportu*, Wydawnictwo Oficyny Wydawniczej Politechniki Warszawskiej, Warszawa 2012.
[12] Jacyna, M., *Modelowanie i ocena systemów transportowych*, Oficyna Wydawnicza Politechniki Warszawskiej, Warszawa 2010.
[13] Lewczuk, K., Żak, J., Pyza, D., Jacyna-Gołda, I., *Vehicle Routing in an Urban Area: Environmental and Technological Determinants*, Urban Transport XIX, Vol. 130, pp. 373-384, WIT Press 2013.
[14] Merkisz, J., Pielecha, J., Radzimirski, S., *Emisja zanieczyszczeń motoryzacyjnych w świetle nowych przepisów Unii Europejskiej*, WKŁ, Warszawa 2012.
[15] Krajowy Ośrodek Bilansowania i Zarządzania Emisjami: *Krajowy bilans emisji SO_2, NO_x, CO, NH_3, NMLZO, pyłów, metali ciężkich i TZO za lata 2010 - 2011 w układzie klasyfikacji SNAP raport syntetyczny*, Warszawa 2013 (www.kobize.pl).
[16] Logistyka transportu towarowego w Europie - klucz do zrównoważonej mobilności, Komunikat Komisji Wspólnot Europejskich do Rady, Parlamentu Europejskiego, Europejskiego Komitetu Ekonomiczno-Społecznego i Komitetu Regionów z dnia 28.06.2006.
[17] Ministerstwo Infrastruktury: Polityka Transportowa Państwa na lata 2006-2025 (http://cms.transport.gov.pl).
[18] Polityka Transportowa Państwa na lata 2005-2020, Rynek Kolejowy, Nr 10, 2004.
[19] www.eea.europa.eu/pl/pressroom/newsreleases/zmniejszenie-kosztow-zdrowotnych-blisko-45.