THE ARCHIVES OF TRANSPORT
Volume 30, Issue 2, 2014

ISSN (print): 0866-9546
e-ISSN (online): 2300-8830
DOI: 10.5604/08669546.1146975

PROECOLOGICAL APPROACH TO MODELLING TRAFFIC ORGANIZATION IN NATIONAL TRANSPORT SYSTEM

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Abstract: *The paper presents a general approach to modelling traffic organization within the network of national transport system and with taking into account environmental aspects. General description of the model and necessary data for modelling are presented. The exact mathematical formulation of constrains and criteria functions assessing quality of traffic organization and taking into account level of emission of harmful compounds of exhaust gases are provided. The assessment of traffic organization in transport network is made in aspect of programming transport system development in ecological terms. Particular attention was paid to technical and ecological features of infrastructure and means of transport. What is important, model uses emission indexes set in real traffic conditions. The example of multi-variant distribution of freight traffic into the transport network is provided. Example was prepared with regard to environmental factors in simulation modelling tool EMITRANSYS developed in PTV VISUM.*

Key words: *ecology of transport, sustainable development, pollutant emission indexes*

1. Introduction

When researching transportation systems, one must keep in mind that transport must be considered in terms of system theory. The main objective of transport system is movement of passengers and cargos of defined types, and characteristics, on different routes, and with different movement parameters. Publications on modelling transport systems ([3], [4], [7] or [15]) indicate that the purpose of study on transport system is proper identification of processes performed in it. Model of transport system should therefore reflect complexity and interdependence of phenomena occurring in the system and its relationship to the environment.

Movement of people and cargo engages number of elements of transport system. It is important to distinguish those elements of system which are involved in movement of passengers and (or) cargos (except those which are the subject of transport). It means that transport system includes elements such as [8]: road network, railways, aviation, and other, like stock of vehicles (cars, buses, trains, airplanes), service stations, freight stations and stops, as well as safety equipment (road signs, traffic lights) along with safety and traffic regulations. Additionally one must consider staff working for proper functioning of transport system.

Due to the difficulty of research on real transport systems appropriate models are constructed. Models reflect complexity and interdependence of phenomena occurring in transport system and its relationship to the environment. The range of system components that must be mapped results from the purpose and scope of carried research.

This paper deals with model of national transport system constructed in a way allowing research on ecology of Polish transport system. Model is a representation of reality or its fragments [2], [6], [15] then if it represents ecological features, it must embrace quantitative and qualitative characteristics of real system, and characteristics relevant to the assessment of level of harmful compounds emitted by means of transport. Model of national transport system is a macro model, therefore it analyses the development of real transport system in the macro scale, so it is not necessary to include all the details of the real system. Constructing a model of national transport system in terms of sustainable development should take into account those aspects that are important in shaping transport policy and understandable to the participant of transport process [24].

Analyse of developed of national transport system should take into account different modes of transport as integral elements of the transportation system and interactions between them [1], [7], [8], [9], [13]. The problems of relations between road transport and other modes (especially rail) are still relevant and important. The European Commission pays particular attention to the need for sustainable transport, including environmentally friendly transportation.

Designing national transport system with regard to environmental aspects is multi-faceted issue. It should take into account:

- the needs of buyers of transport services,
- technical potential of transportation providers, including their ability to make changes,
- transport infrastructure and vehicles,
- solutions for traffic management in particular areas and regions of transport network,
- transport policy of a country or region,
- ecological conditions of functioning and development of transport.

The main factor leading to the development of techniques and technology in all areas of the industry is the need to reduce its negative impact on the environment. Designing proecological transport system is very complicated issue and forces designers and analysts to look for new solutions in that area. This is related to growing awareness of threats connected to increasing emissions of harmful compounds of exhaust gases from transport.

The negative impact of transport on the environment is primarily a [5], [11]:

- greenhouse gases emissions that contribute to climate change,
- emission of air pollutants affecting the health of people and the natural environment,
- taking over valuable nature areas and cutting their continuity (fragmentation) by newly-build strings of technical infrastructure, contributing to loss of biodiversity,
- noise emission threatening human health.

Growth trends in passenger and freight transport make the consequences of actions taken to reduce those negative effects partly mitigated by increased transport volumes. Many analysis show [1], [2], [6], [7], [11], [14], [21], [22] that road transport has the greatest share in total emissions into the environment. The continuing predominance of road transport in total transport volume makes difficult achieving desired effects of taken actions.

Current research on emissivity of road vehicles are generally carried out in two variants:

- comparative studies of pollutant emissions from cars and trucks, or directly from internal combustion engines. This research are carried on engine or chassis dynamometer using measuring equipment and instruments used on on-board;
- studies to estimate emission factors of vehicles in real traffic conditions by on-board method and relating them to the emission limits (Euro). Measured indicators allow then evaluation of approximate exhaust gas emissions of these vehicles in real traffic conditions.

This paper presents an approach to modelling proecological national transport system. These are thoughts developed during the project EMITRANSYS realized by two teams: Department of Logistics and Transport Systems at the Faculty of Transport of Warsaw University of Technology. and Institute for Internal Combustion Engines, Faculty of Machines and Transportation of Poznań University of Technology.

Measurable result of EMITRANSYS project was obtaining emission factors on the base of research carried out in real conditions [17], [19], [20]. Authors propose implementation of emission factors denoting increase (or decrease) emissions in real traffic conditions in relation to certification test. Such indicator, for each harmful compound is defined as follows:

$$k_s = \frac{E_{rz,s}}{E_{N,s}}$$

s – harmful compound, for which emission factor was specified,

$E_{rz,s}$ – pollution emissions obtained in real conditions [g/km] for s-th compound,

$E_{N,s}$ – pollution emissions according to exhaust emissions standards [g/km].

Proposed correction factors will adapt approval emission values obtained in certification tests into real conditions of vehicle operating. Coefficients, referred as „*k*", must be unitless and defined for different emission classes of vehicles:

- cars and vans (up to 3.5 tonnes) for which emission standards are defined in grams per kilometer [g/km],
- trucks and off-road vehicles for which emission standards are defined in grams per kilowatt-hour [g/(kWh)].

Determination of emissivity in road conditions and comparing it with values obtained on chassis dynamometer during certification test allowed to determine emission factor, which is used to answer the question: does emissions in road conditions is comparable to emission obtained in the certification test? (see [5], [18]).

2. Elements of proecological transportation system model

The model of national transport system should take into account requirements of physical transport processes [12], [23]:

- lasting objects: roads, railways, inland water channels, service stations for passenger and freight transport (eg. railway stations, terminals, airports, etc.) with specified characteristics,
- vehicles – means of transport that use transport infrastructure,
- people forming crew of transportation system, which use technical equipment of the system for the movement of passengers and cargo,
- organizational system ensuring correct use of technical equipment of transport.

Model of proecological transport system must have properties allowing studies on modal interaction with regard to the level of emissions. Therefore, to examine modal split, proecological transport system should imitate behaviour of real system with appropriate precision to research relations between tasks, equipment and organization of the system with accuracy comparable to observed in actual system.

The model of proecological transport system has been defined taking into account the following basic elements:

- **set of types of vehicles** used to perform transport tasks, described as records of database,
- **structure of transport network** depicting links between origin, intermediate, and destination points for passenger and cargo streams,
- **characteristics of network elements** representing actual properties of vehicles and transport connections (characteristics derived from existing databases, especially characteristics assigned to nodes of the network resulting from the treatment of vehicles, where mode of transport is changed, and characteristics assigned to edges of network resulting from movement of vehicles);
- **size of transport tasks** identified at the input to the system (demand for transport services reported by purchasers of services);
- **organization** conceived as a way to carry traffic via the transport network from input places to output places with regard to emission levels, stock of means of transport, infrastructure condition and economic conditions. Organization can differ according to investigated scenario of system development.

Assuming that a set of types of vehicles is marked as **ST**, structure of transportation system is marked as **GE**, a set of characteristics of means of transport and structural elements is marked as **FE**, matrix of tasks performed by system is marked as **QE**, traffic organization on the network is marked as **OE**, then **M**odel **E**nvironmentally friendly **T**ransportation **S**ystem (MEST) can be written as an ordered five:

$$\mathbf{MEST} = \langle \mathbf{ST}, \mathbf{GE}, \mathbf{FE}, \mathbf{QE}, \mathbf{OE} \rangle$$

Modeling national transport system with regard to environmental aspects requires:

1. identification of transport network structure,
2. identification of means of transport with a clarification of their characteristics,
3. description of network nodes by parameters necessary to carry out modal-interaction,
4. description of transport network links by parameters necessary to carry out modal-interaction,
5. identification of tasks directed from the environment to the transport system,
6. identification of routes to move traffic (execution of transport tasks)
7. definition of boundary conditions and implementation constraints for particular modes and means of transport,
8. definition of evaluation indicators and criteria for assessment of level of harmful gases emitted by means of transport,
9. proposing scenarios of transport system development with regard to environmental aspects,
10. implementation of the model in PTV VIUSUM to gain tool for simulation research on transport systems,
11. preparation of databases covering structure and characteristics of vehicles, characteristics of transport connections, and characteristics of nodal elements of transport network,

12. setting scenarios of traffic distribution in transport network with regard to different constrains
13. carry out multivariate analyzes of distribution of traffic into transport network,
14. elaboration of guidelines for development of national transport system for various decision-making situations.

Taking into account above points, proper planning of transport system development with regard to environmental aspects means determining relations between forecasted transport tasks entering the system, its equipment and the cost of tasks realization. The cost of tasks realization is determined by level of emissions of harmful exhaust gases from means of transport. In this regard, constructed model must map relations between transport network structure, its parameters and level of emissions of harmful exhaust gases, especially from road transport. It also maps modal split in aspect of functional relation between structure and parameters of road traffic and environmental pollution.

Proper planning of the development of transport system should lead to reduction of environmental degradation and thus to adjustment of elements of transport infrastructure to reported demand for transport. Proposed model of transport system embraces not only problems of resources allocation for modernization of infrastructure, but also the choice of variant of infrastructure modernization reducing emissions, especially in protected areas.

Analysis of transport system development can be done on the basis of traffic distribution on transport network under different boundary conditions and different criteria [11]. The analyses of modal split reveal that transport network infrastructure characteristics are determined and shaped by transport administrators. Studies on the effect that different strategies or transport policies undertaken by authorities have on behaviour of transport service providers are conditioned by disposal by authority of appropriate research tool.

3. Formal description of the structure of national transport system

As it was stated before, structure of transport network represents existing and planned road, railway and other transport connections between places of origin, processing places, and destination points. It also defines possible relations between origin and destination points through which goods or passengers are moved. Proper realization of material and passenger flows relies on the following types of infrastructure:

- linear: existing transport links (e.g. railway, roads),
- nodal: 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:

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

where:

WE – set of nodes representing origin and destination points together with intermediate nodes for goods and passenger flows, $\boldsymbol{WE} = \{1, ..., a, \ldots, i, i', ..., b, \ldots, WE\}$,

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***:

$$\boldsymbol{WE} = \boldsymbol{N} \cup \boldsymbol{P} \cup \boldsymbol{O}$$

To simplify the calculations it was assumed that sets ***N***, ***P***, ***O*** are pairwise 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*).

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 $p \in \boldsymbol{P}^{ab}$. It is assumed that:

$$\forall (a,b) \in \boldsymbol{E} \quad \exists p \in \boldsymbol{P}^{ab}$$

To enable a multi-variant multimodal interaction, geographic areas must be associated with 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.

4. Basic characteristics of means of transport and elements of transport infrastructure

Shaping environmentally friendly transport system requires inclusion in the model parameters of technical means of transport, which influence level of emissions, and infrastructure parameters having significant impact on the performance of moving vehicles. To assess impact of technological and organizational solutions on emission and on necessary expenditures, model also takes into account economic parameters of road transport and road infrastructure.

The individual elements of the model are described in details in [23]. Since the study relates to emissions of harmful compounds of exhaust gases produced by transport, it is important to define sets of types of vehicles and their characteristics. For the purpose of research it was defined:

- set $\boldsymbol{S}$, $\boldsymbol{S}=\{1, ..., s, \ldots, S\}$ of harmful compounds, wherein: $s = 1$ – carbon monoxide CO, $s = 2$ – hydrocarbons HC, $s = 3$ – nitric monoxide NO, $s = 4$ – nitric dioxide NO_2, $s = 5$ – particulate matters PM, $s = 6$ – carbon dioxide CO_2,
- set $\boldsymbol{ST}$, $\boldsymbol{ST}=\{1, ..., st, \ldots, ST\}$ of types of means of transport, discreted according to mode of transport, purpose, and loading capacity. Additionally possible types of engines (according to type of fuel and characteristics) are given $\boldsymbol{RSP} = \{rsp\text{: } rsp = 1, 2, 3, 4\}$, as well as EURO standards of emission $\boldsymbol{NEU}=\{neu\text{: } neu = 0, 1, 2, 3, 4, 5, 6\}$. [17], [19].

Considering above, each type of vehicle has been characterized by vector of technical, ecological and economical parameter:

$$\mathbf{v}(st) = [rsp(st), neu(st), q(st), m(st), c(st), em(s, st)],\quad s \in \boldsymbol{S}$$

where:

$rsp(st)$ – type of engine of st-th type of vehicle,
$neu(st)$ – EURO standard of st-th type of vehicle,
$q(st)$ – loading/cubic capacity of st-th type of vehicle,
$m(st)$ – mode of transport (passenger/freight, railway/road) of st-th type of vehicle,
$c(st)$ – unit cost of transport by st-th type of vehicle.
$em(s,st)$ – unit emission of s-th type harmful compound from st-th type of vehicle.

To implement a model in PTV VISUM, a database **BST** of means of transport was developed. The database has a form of a vector of three components, $\mathbf{BST} = [\mathbf{S}, \mathbf{ST}, \mathbf{v}(st)],\ st \in \boldsymbol{ST}$.

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

$d(i,i')$ – flow capacity of section (i, i'),
$l(i,i')$ – length of section (i, i'),
$v^{max}(i,i')$ – speed limit on section (i, i'),
$neu(i,i')$ – permissible EURO standard on section (i, i'),
$c(st, i, i')$ – the cost of travel on section (i, i') by st-th type of vehicle,
$q^{max}(i, i')$ – section (i, i') throughput,
$q(i,i')$ – tonnage limitation on a section (i, i'),
$ob(i, i')$ – network area to which the section (i, i') is attributed.

These allowed description of each section by a vector $\mathbf{w}(\boldsymbol{i}, \boldsymbol{i'})$:

$$\mathbf{w}(i, i')=[q^{max}(i, i'), q(i, i'), d(i, i'), l(i, i'), v^{max}(i, i'), neu(i, i'), [c(st, i, i'):], ob(i, i')]$$

In addition, to make the modal interaction in aspect of emission, additional characteristics must be defined:

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

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 in VISUM.

Database of characteristics of means of transport and structural elements of transport system **BFE** has been constructed as a vector: **BFE** = [**FLE**, **FWE**, **BST**], where **FLE** database is for connections, **FWE** database is for transport nodes, and **BST** is a database of transport resources (selected vehicles).

5. Transportation tasks

To determine the size of transport tasks, appropriate segments of demand for freight and passenger transport must be defined (see [16]). If *spt* denotes a fixed segment of demand for freight transport, then a set of segments of demand for freight transport takes form: $\boldsymbol{SPT} = \{1, 2, ..., spt, ..., SPT\}$. Similarly, for the carriage of passengers, *spp* denotes segment of demand, and set of segments of demand for passenger transport is written as $\boldsymbol{SPP}=\{1, 2, ..., spp, ..., SPP\}$.

Generally, size of transport tasks in transport system model is given by two-element vector $\boldsymbol{QE}$, $\boldsymbol{QE}$ = [**X1**, **X2**], wherein the first array element **X1** is demand for freight transport, and second element is a matrix **X2** of demand for passenger transport. **X1** matrix is composed of elements $x1(a, b, spt)$ interpreted as a quantity of goods of *spt*-th segment of demand, which must be moved in relation (a, b), so $\mathbf{X1} = [x1(a, b, spt)]$. Matrix **X2** comprises elements $x2(a, b, spp)$ interpreted as number of passengers in *spp*-th segment of demand, which must be moved in relation (a, b), so $\mathbf{X2} = [x2(a, b, spp)]$.

6. Optimization task of traffic distribution as the organization of movement in national transport system

Generally, organization means fitting potential of transport system (its equipment) to realization of tasks while technical, economic and ecological constrains are satisfied and evaluation criteria are maximized [8] Traffic organization in national transport system results from distributing passenger and freight flows on elements of multimodal transport network and on means of transport [1]. Thus, organization determines desired traffic streams and way of performing transport tasks due to adopted criteria.

Organization of traffic in transport network is nothing but loading transport links different vehicles as a consequence of satisfying demand for transport and up to constrains. To find optimal organization, according to accepted quality criteria, the optimization task – appropriate for decision situation – must be formulated. Models of development of proecological transport system base on criteria that allow setting vehicles movement in elements of transport network under technical, economic and ecological constrains, that minimize levels of emission or indirect costs embracing that aspect.

Thus, the problem is to determine number $xt(p, a, b, st)$ of *st*-th means of transport servicing cargo flows and number $xp(p, a, b, st)$ of vehicles carrying passengers and moving on *p*-th transport routes in relations (a, b), to minimise value $\psi(s, \mathbf{v}(\mathbf{st}), p, (a, b))$ specifying size of emission of *s*-th compounds related to structure of vehicles (including engine type and EURO emission standard).

Decision variables $xt(p, a, b, st)$ and $xp(p, a, b, st)$ are stored into arrays **XT** and **XP** and described as a vector of decision variables $\mathbf{X} = [\mathbf{XT}, \mathbf{XP}]$.

If model considers modernization of existing facilities or building new infrastructure, decision variables are investment expenditures spent on upgrading existing or building new infrastructure - $f(i, i')$. Variables $f(i, i')$ are denoted as matrix **XF**.

Assessment of solutions (quality of organization) in national transport system is performed by one of the criterion function:

a) level emission of harmful exhaust components:

$$\forall s \in \boldsymbol{S}$$

$$\sum_{st\in \boldsymbol{ST}} \sum_{(i,i')\in \boldsymbol{LE}} \sum_{(a,b)\in \boldsymbol{E}} \sum_{p\in \boldsymbol{P}_{i,i'}^{ab}} \left[xt(p,a,b,st)+xp(p,a,b,st)\right]\cdot \cdot em(s,st,i,i')\cdot \psi a(s,st,p,a,b) \longrightarrow \min$$

b) cost of transport:

$$\sum_{st\in \boldsymbol{ST}} \sum_{(i,i')\in \boldsymbol{LE}} \sum_{(a,b)\in \boldsymbol{E}} \sum_{p\in \boldsymbol{P}_{i,i'}^{ab}} \left[xt(p,a,b,st)+xp(p,a,b,st)\right]\cdot \cdot c(st,i,i') \longrightarrow \min$$

c) analyses of investment expenditures for modernization of transport infrastructure leads to criteria function:

$$\sum_{st\in \boldsymbol{ST}} \sum_{neu\in \boldsymbol{NEU}} \sum_{(i,i')\in \boldsymbol{LE}} \sum_{rsp\in \boldsymbol{RSP}} \sum_{(a,b)\in \boldsymbol{E}} \left\{ \begin{array}{l} \sum_{p\in \boldsymbol{P}_{i,i'}^{ab}} \left[\begin{array}{l} xt\left(p,a,b,st,rsp,neu,(i,i')\right)+ \\ xp\left(p,a,b,st,rsp,neu\right) \end{array} \right]\cdot \\ l(i,i')c\left(i,i',st,rsp,f(i,i')\right)+f(i,i') \end{array} \right\} \longrightarrow \min$$

d) external costs of transport [26]:

$$Kz(i,i') = \sum_{(i,i')\in \boldsymbol{LE}} \sum_{st\in \boldsymbol{ST}(i,i')} \left(\sum_{spp\in \boldsymbol{SPP}} xt(i,i',st,spp)\,\eta(i,i',st,spp) + \sum_{spt\in \boldsymbol{SPT}} xp(i,i',st,spt)\,\eta(i,i',st,spt) \right) \longrightarrow \min$$

where $\eta(i, i', st, spp)$ – index of external costs.

According to above findings about structure of transport network, characteristics of transport links and transshipment points/hubs, means of transport and their characteristics, the optimization task of traffic distribution on transport network to model proecological transport system is formulated as follows:

For given:

– **QE** = [**X1**, **X2**], ***GE, FE, ST*** (given as databases **BFE=[FLE, FWE, BST]**), including:

- **v**(*st*) vectors of vehicles characteristics,
- **w**(*i*, *i*') vectors of transport links characteristics,
- *em*(*s, st, neu, rsp*) – level of emission of *s*-th harmful component of exhaust gases by *st*-th type of vehicle with *rsp*-th type of engine in *neu*-th standard of emission per unit of distance travelled,
- $lp^{max}(st, neu(st), rsp(st))$ – number of available *st*-th type vehicles with *rsp*-th type engines in a *neu*-th EURO standard.
- *qt*(*st*, *spt*) and *qp*(*st*, *spp*), the maximum capacity of means of transport assigned to transport passenger or cargo from various segments of demand.

Taking into account auxiliary variables relating to:

– traffic distribution for the various segments of demand for cargo and passenger transport onto transport network *x*1(*p*, *a*, *b*, *spt*, *st*) and *x*2(*p, a, b, spp, st*),

– traffic volume of different types of vehicles on transport connections: *xt*(*st*, *i*, *i*'), *xp*(*st*, *i*, *i*'),

– traffic of different types of vehicles: *xt*(*n*(*st*), *st*, *i*, *i*'), *xp*(*n*(*st*), *st*, *i*, *i*') – binary variables,

one must set the elements of matrixes:

XT = [*xt*(*p*, *a*, *b*, *st*)] **XP** = [*xp*(*p*, *a*, *b*, *st*)]

with regard to constrains:

1. fulfilling demand for transport **QE** = [**X1**, **X2**]:

$$\forall (a,b)\in \boldsymbol{E} \; \forall spt\in \boldsymbol{SPT}$$

$$\sum_{p\in \boldsymbol{P}^{ab}} \sum_{st\in \boldsymbol{ST}} x1(p,a,b,spt,st) = x1(a,b,spt)$$

$$\forall (a,b)\in \boldsymbol{E} \; \forall spt\in \boldsymbol{SPP}$$

$$\sum_{p\in \boldsymbol{P}^{ab}} \sum_{st\in \boldsymbol{ST}} x2(p,a,b,spp,st) = x1(a,b,spp)$$

2. not exceeding disposed number of vehicles

$$\forall st\in \boldsymbol{ST}$$

$$\sum_{(a,b)\in \boldsymbol{E}} \sum_{p\in \boldsymbol{P}^{ab}} \left[xt(p,a,b,st)+xp(p,a,b,st)\right] \le \sum_{neu(st)\in \mathbf{NEU}(st)} \sum_{rsp(st)\in \mathbf{RSP}(st)} lp^{max}\left(st,neu(st),rsp(st)\right)$$

3. not exceeding technical capacity of transport links:

$$\forall (i,i')\in \boldsymbol{LE}^{PP} \quad \sum_{st\in \boldsymbol{ST}} \left[xt(st,i,i')+xp(st,i,i')\right] \le d(i,i')$$

4. forbidden movement of selected types of vehicles on transport links:

$$\text{if} : st \notin \boldsymbol{ST}(i,i') \Rightarrow xt(st,i,i') = 0 \wedge xp(st,i,i') = 0 \quad st \in \boldsymbol{ST} \;\; (i,i') \in \boldsymbol{LE}$$

5. forbidden movement of selected types of vehicles on transport links according to EURO emission standard:

$$\text{if} \quad nes(n(st),st) \notin \boldsymbol{NEU}(i,i') \Rightarrow xt(n(st),st,i,i') = 0 \wedge xp(n(st),st,i,i') = 0 \quad (i,i') \in \boldsymbol{LE}, \quad st \in \boldsymbol{ST}, \quad n(st) \in \boldsymbol{N}(st)$$

6. not exceeding permissible total weight of means of transport:

$$\text{if} \quad DMC(n(st),st) > \boldsymbol{DMC}(i,i') \Rightarrow xt(n(st),st,i,i') = 0 \wedge xp(n(st),st,i,i') = 0 \quad (i,i') \in \boldsymbol{LE}, \quad st \in \boldsymbol{ST}, \quad n(st) \in \boldsymbol{N}(st)$$

7. not exceeding permissible axle load by means of transport:

$$\text{if} \quad qosi(n(st),st) > Qosi(i,i') \Rightarrow xt(n(st),st,i,i') = 0 \wedge xp(n(st),st,i,i') = 0 \quad (i,i') \in \boldsymbol{LE}, \quad st \in \boldsymbol{ST}, \quad n(st) \in \boldsymbol{N}(st)$$

8. not exceeding vertical gauge by means of transport:

$$\text{if} \quad h(n(st),st) > H(i,i') \Rightarrow xt(n(st),st,i,i') = 0 \wedge xp(n(st),st,i,i') = 0 \quad (i,i') \in \boldsymbol{LE}, \quad st \in \boldsymbol{ST}, \quad n(st) \in \boldsymbol{N}(st)$$

9. not exceeding horizontal gauge by means of transport:

$$\text{if} \quad b(n(st),st) > B(i,i') \Rightarrow xt(n(st),st, \quad i,i') = 0 \wedge xp(n(st),st,i,i') = 0 \quad (i,i') \in \boldsymbol{LE}, \quad st \in \boldsymbol{ST}, \quad n(st) \in \boldsymbol{N}(st)$$

10. number of means of transport of different types on transport links:

$$\forall (i,i') \in \boldsymbol{LE}^{PP} \; \forall st \in \boldsymbol{ST}$$
$$\sum_{n(st) \in \mathbf{N}(st)} xt(n(st),st,i,i') = xt(st,i,i')$$
$$\sum_{n(st) \in \mathbf{N}(st)} xp(n(st),st,i,i') = xp(st,i,i')$$

11. binarity of decision variables $xt(n(st), st, i, i')$ and $xp(n(st), st, i, i')$:

$$\forall (i,i') \in \boldsymbol{LE}^{PP} \; \forall st \in \boldsymbol{ST} \; \forall n(st) \in \boldsymbol{N}$$
$$xt(n(st),st,i,i') \in \{0, 1\}$$
$$xp(n(st),st,i,i') \in \{0, 1\}$$

12. non-negative traffic:

$$\forall (a,b) \in \boldsymbol{E} \; \forall p \in \boldsymbol{P}^{ab} \; \forall spt \in \boldsymbol{SPT} \; \forall st \in \boldsymbol{ST}$$
$$x1(p,a,b,spt,st) \geq 0$$
$$\forall (a,b) \in \boldsymbol{E} \; \forall p \in \boldsymbol{P}^{ab} \; \forall spt \in \boldsymbol{SPP} \; \forall st \in \boldsymbol{ST}$$
$$x2(p,a,b,spp,st) \geq 0$$

13. traffic additivity:

$$\forall st \in \boldsymbol{ST} \; \forall (i,i') \in \boldsymbol{LE}^{PP}$$
$$xt(st,i,i') = \sum_{(a,b) \in \boldsymbol{E}} \sum_{p \in \boldsymbol{P}_{i,i'}^{ab}} xt(p,a,b,st)$$
$$xp(st,i,i') = \sum_{(a,b) \in \boldsymbol{E}} \sum_{p \in \boldsymbol{P}_{i,i'}^{ab}} xp(p,a,b,st)$$

14. continuity of traffic in flow sources:

$$\forall a \in \boldsymbol{N} \; \forall st \in \boldsymbol{ST} \; \forall i \in \boldsymbol{\Gamma}(a)$$
$$xt(st,a,i) = \sum_{b \in \boldsymbol{O}} \sum_{p \in \boldsymbol{P}^{ab} : (a,i) \in \boldsymbol{LE}^{p,ab}} xt(p,a,b,st)$$
$$xp(st,a,i) = \sum_{b \in \boldsymbol{O}} \sum_{p \in \boldsymbol{P}^{ab} : (a,i) \in \boldsymbol{LE}^{p,ab}} xp(p,a,b,st)$$

where $\boldsymbol{\Gamma}(a)$ is a set of consequent nodes of source a.

15. continuity of traffic in intermediate nodes:

$$\forall i \in \boldsymbol{P} \; \forall st \in \boldsymbol{ST}$$
$$\sum_{i' \in \boldsymbol{\Gamma}^{-1}(i)} xt(st,i',i) = \sum_{i' \in \boldsymbol{\Gamma}(i)} xt(st,i,i')$$
$$\sum_{i' \in \boldsymbol{\Gamma}^{-1}(i)} xp(st,i',i) = \sum_{i' \in \boldsymbol{\Gamma}(i)} xp(st,i,i')$$

where $\boldsymbol{\Gamma}^{-1}(i)$ is a set of precedents for node i, and $\boldsymbol{\Gamma}(i)$ is a set consequent nodes of i.

16. continuity of traffic in terminating nodes

$$\forall b \in \boldsymbol{O} \; \forall st \in \boldsymbol{ST} \; \forall i \in \boldsymbol{\Gamma}^{-1}(b)$$
$$xt(st,i,b) = \sum_{a \in \boldsymbol{N}} \sum_{p \in \boldsymbol{P}^{ab} : (i,b) \in \boldsymbol{LE}^{p,ab}} xt(p,a,b,st)$$

$$xp(st,i,b)=\sum_{a\in \boldsymbol{N}}\sum_{p\in \boldsymbol{P}^{ab}:(i,b)\in \boldsymbol{LE}^{p,ab}} xp(p,a,b,st)$$

where $\Gamma^{-1}(b)$ is a set of precedents of terminating node b.
The aim is to find such an organization of material and passenger flows in the national transportation network that minimizes one on presented before criteria functions.

7. Examples of practical applications of model of transport system

Model MEST implemented in VISUM (EMITRANSYS model) (see detailed papers like [7], [25]) was used to simulate multivariant distribution of cargo streams on transport network of Poland according to three criteria: minimizing transport time (MC), minimizing travelled distances (MD) and minimizing cost of transport (MK). Distribution was made for loads belonging to 14 cargo groups like: chemicals, wood, coke, machinery, furniture, metals, non-metallic products, agriculture, ores, food, transport equipment, raw materials, coal and textiles. For each analyzed variant of streams distribution the transport volumes were calculated for rail and road transport (table 1).

Tabela 1. The share of transport modes in total transport volume [10]

Mode of transport	Transport volume [tkm]		
	MK	MD	MC
Railway	129406371	106279883	43106396
Road	433467419	432543848	533747468
Share in total transport volume [%]			
Railway	23%	20%	7%
Road	77%	80%	93%

Determination of harmful emission into the environment was made for road transport mode. Transport was performed with three types of vehicles - vans, trucks without trailers and trucks with trailers. Calculations are based on data about number of vehicles of different types in segments of transport network resulting from National Traffic Measurements 2010 (an average daily traffic measurement), and their average capacity (determined on the base of data presented in Transportation Activity Results 2012).

Various types of vehicles on sections of transport network, and their basic movement characteristics were used to estimate emissions of harmful compounds of exhaust gases like CO_2, CO, HC, NO_x, PM by road freight transport. Calculations were done by HBEFA module provided by PTV VISUM. The emissions of harmful substances by the transport system, expressed in grams, is presented in table 2.

Table 2. The level of contamination by harmful exhaust compounds from road freight transport [10]

Pollutant	Pollution level [g]		
	MC	MD	MK
CO_2	5644560017	4705146216	4442068514
CO	81141408	67576488	63600631
HC	6775942	5616097	5251553
NO_X	25611104	21314996	20194327
PM	2089668	1745207	1646830

The levels of each pollutant in g/km on individual sections of road network are shown in Fig. 15, 16 and 17.

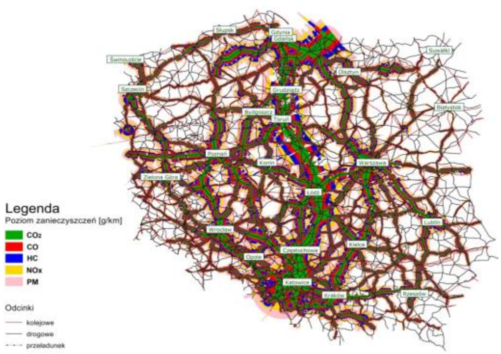

Fig. 15. The level of emissions according to criterion of minimal transport time (MC)

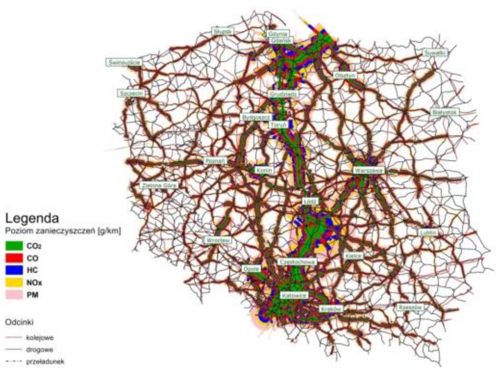

Fig. 16. The level of emissions according to criterion of minimal travelled distances (MD)

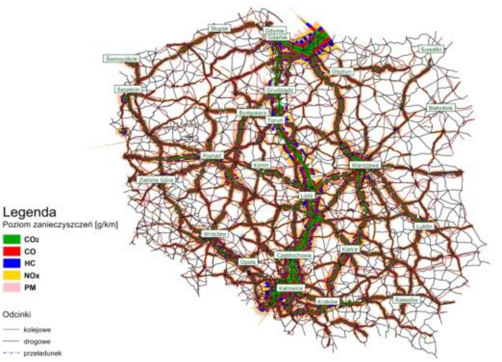

Fig. 17. The level of emissions according to criterion of minimal costs (MK)

8. Conclusions

Designing proecological transport system aims in reducing negative effects of transport on the environment. Research carried out EMITRANSYS project allowed to assess the impact of harmful exhaust emissions on environmental pollution.

As indicated in the article, modeling traffic organization in national transport system in terms of ecology is multi-faceted decision-making problem. All individual modes of transport are integral elements of national transportation system as whole and development of each of them has certain effects in other sectors.

Significant aspect of EMITRANSYS project was development of functional relations between level of emissions and technical parameters of vehicles as well as sub-technical factors like demand for transport (affecting vehicles capacity usage) or infrastructure conditions limiting velocity, or transshipment possibilities. Gathered dependences were used in a simulation model to distribute traffic on the transport network or to analyze modal split.

Mathematical model for development of national transport system and its implementation in the form of EMITRANSYS model are tools to assess impact of transport on the environment and to evaluate effectiveness of undertaken initiatives like changes in organization of vehicles movement or modernization of regulatory framework relating to the transport.

Model allows for determination of level of harmful exhaust gases emissions. It takes into account factors like: cost and time of transportation and the current or planned infrastructure capacity. EMITRANSYS model uses indicators derived from real traffic measurements representing mathematically level of harmful emissions as a function of technical parameters of road infrastructure, as well as organizational functions and parameters of transport system maintenance. It can be used to simulation studies on the impact of road transport on the environment.

Acknowledgment

The research is carried out under the project "Proecological transport system designing" (EMITRANSYS) funded by the National Centre for Research and Development.

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