ISSN: 1231-4005
e-ISSN: 2354-0133
ICID: 1130519
DOI: 10.5604/12314005.1130519

CHOSEN ASPECTS OF SIMULATION MODEL TO DESIGNING PRO-ECOLOGICAL TRANSPORT SYSTEM

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Abstract

Paper presents simulation model of pro-ecological transport system (PTS). Model allows computational experimentation and inference on transport modal split and emission of pollution in a national scale. The characteristics describing infrastructure, vehicles, and harmful compounds emission are given. Model is implemented in VISUM – a tool supporting planning of transport processes as well as analysis and designing of transport systems. The demand for transport services and emission of exhaust gases components are reflected in model of pro-ecological transport system of Poland. In particularly, Representation of model of pro-ecological transport system, transport sub-systems and segments of demand in freight transport in simulation model of PST, detailed assumptions of on-board measurements for Mercedes C200, detailed results of on-board measurements of pollutants, CO2 emission in function of instantaneous velocity and acceleration, representation of pollutants emitted by freight transport in Poland, as well general assumptions for designing simulation model of pro-ecological transport system and material and passenger flows distribution and the pollution emission are presented in the paper.

Keywords: *pro-ecological transport system, PTV VISUM, EMITRANSYS, transport system modelling*

1. Introduction

The impact of air quality on human health has been widely studied [19]. In Europe, atmospheric pollution is regarded as one of the environmental factors that have the greatest impact on human health. Up to now, much attention has been devoted to urban air pollution [10, 15], and to global pollution circulation [16, 17], but only little attention was paid to supporting decision-making in planning pro-ecological development of large-scale transport systems. Development of systems like national transport system must be planned and controlled centrally under multicriteria evaluation taking into account economic, technical and social necessities, and above all environmental factors. Planning infrastructural investments on that scale requires efficient tools orienting them in a whole system and reconnoitering plausible aftermath. National transport system is considered as *pro-ecological* if its development accommodates not only economic and social results, but environmental aspects too.

Considering above, the EMITRANSYS project was launched. Project aims in gaining a simulation tool to carry out computational experiments on the impact of modal split, material and passenger flow volumes, structure of transport network, or types of vehicles on emission of pollutants like CO, HC, NO, NO_2, PM, and CO_2 in a large scale from road vehicles and indirectly railway. Emission patterns for various vehicles and in different travel, conditions are results of empirical experiments in real traffic conditions.

The tool can be potentially used to analyse scenarios of transport system development for a variable demand conditions, and different external or internal determinants. Simulation model allows preparing a data to estimate the impact that transport has on a natural environment in various scenarios.

The simulation model can be used to examine transportation system (e.g. Polish) as a whole or – through additional detailing – implemented for research on a regional scale. The tool can be used for planning changes in parameters of infrastructure, or for assess adding new sections, roads and railways to the transport network. It can support decision making to increase attractiveness of some modes of transport, or to restrict using transport network in the areas under special protection (national parks, natural monuments, city centres, etc.). Thus, it is an important tool for strategic decision-making in the development of the transport system in terms of its impact on the environment.

Paper presents framework, selected details and preliminary results of simulation model of Pro-ecological Transport System (PTS) on example of Poland.

2. Problems of ecological transport systems

Modelling pro-ecological transport system, and subsequently its simulating, requires relevant data about emission in transport. Road transport is a main source of pollution, so it is well worked on in the literature (e.g. [6]). For NO2, road traffic is of special relevance because it typically accounts for the major proportion of NO_x emissions, and hence of NO_2 concentrations [18].

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 measure and driving protocols (e.g. [7]).

Affum, *Brown*, and *Chan* [1] present a GIS-based transport add-on environmental modelling system designed to evaluate the environmental consequences of road traffic in urban areas. The system integrates information about traffic with information about land use, to provide the input data to a range of commonly used models that estimate pollution from a road traffic system. Model allows planners having rapid feedback on the environmental effects of road transport network scenarios that are being tested.

Chiquetto and *Mackett* [5] prove that transport policies have significant impacts on the environment. They implement the road traffic assignment model, in conjunction with an air pollution dispersion model, to the urban road network of selected city. One model simulates the traffic flow conditions; whereas the second one estimates the concentration of five main traffic pollutants around road junctions. Actual vehicle exhaust emission rates are input into the dispersion model, as a function of fuel type, fitting of catalytic converters and typical driving operating patterns.

Bai, *Chiu* and *Niemeier* [3] present a modelling framework that consistently provides both trip-based and link-based vehicle miles travelled speed distributions, and quantify the effects of using trip-based versus link-based travel data on regional peak period emission inventories. *Russo* and *Musolino* [15] present the transport macro-model consisting of three main components, namely the transport supply model, travel demand model and the assignment model. assignment model has travel demand to be dependent on activity flows and transport utilities.

Merkisz-Guranowska et al. [12] describe steps and basic guidelines related to the creation of a sustainable transport systems model. The model may be used to design environmentally friendly transport systems that reduce negative environmental impact from vehicles and guarantee the efficient use of the road transport network.

Merkisz et al. [11] develop the methodology of exhaust emission measurements in the development of sustainable road transport. Their work bases on real-time experiments and long-term on-board analyses to gain universal emission characteristics for different traffic conditions including cold starts, long and short trips or congestion. This research is done to answer the question of real emission levels compared with EURO standards. EMITRANSYS project adapt this methodology to obtain broad vehicles characteristics opportunely for simulation.

3. The general assumptions for designing simulation model of pro-ecological transport system

The three main components of the transport-modelling framework are the transport supply model, the travel demand model and the assignment model. In the literature, a large variety of models belonging to each component is found. Detailed state-of-the-art analyses are presented in *Cascetta* [4]. Forming pro-ecological transport system (PTS) requires inclusion of relationship between structures of transport network, the technical parameters influencing traffic, vehicles, and their operation parameters, and harmful emission levels. Therefore a model of PTS, as an evolved version of Model of logistics system of Poland (see [8, 9, 20]) embraces not only freight, but passenger transport too, and compiles them to find resultant emissions. Confronting technical parameters of vehicles and road infrastructure with demand for transport services leads to gaining characteristics of traffic conditions which are base to model emission, performance of transportation system, and to ask „what if“ questions for system development. A schematic representation of model of PTS is given on Fig. 1.

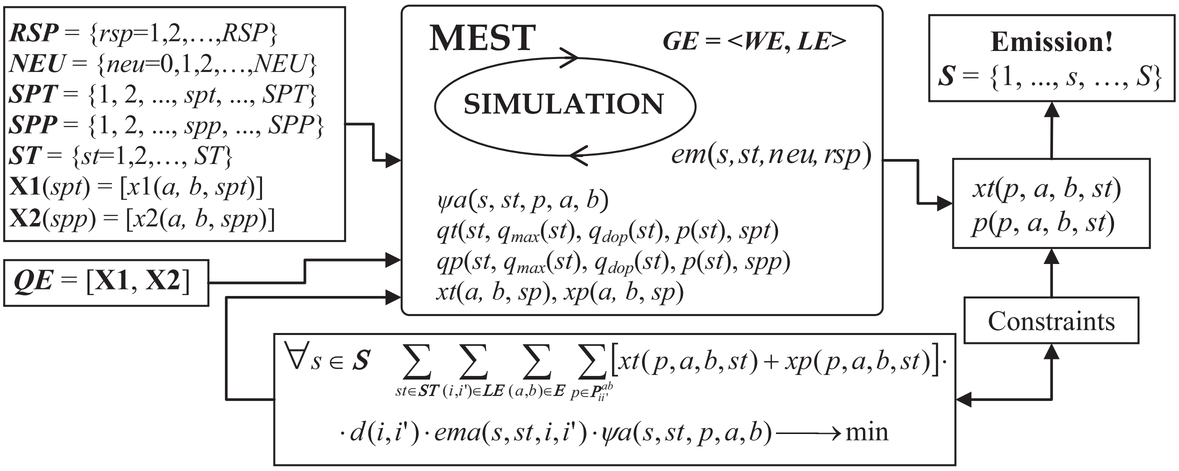

Fig. 1. Representation of model of pro-ecological transport system

According to the type of engine, EURO standard, loading, and traffic conditions, means of transport emit specific pollution. Set of pollution types is marked as $\boldsymbol{S} = \{1, ..., s, \dots, S\}$. Taking into account previously defined sets: $\boldsymbol{ST}$, $\boldsymbol{RSP}(st)$ and $\boldsymbol{NEU}(st)$, the general functions of unit emission $em(s, st, neu(st), rsp(st), i, i')$ are given. When structure of vehicles and their engines is known in given period of time, the projection of function $em(s, st, neu(st), rsp(st), i, i')$ into a form $ema(s, st, i, i')$ is possible.

The influence of engine type, EURO standard and the length of travelled p-th path in relation (a, b) on emission is described by coefficients $\psi(s, st, neu(st), rsp(st), p, a, b)$. After projection, they take a form of $\psi a(s, st, p, a, b)$.

When model parameters are defined as above, the problem of developing pro-ecological transport system is reduced to searching for the values of decision variables $xt(p, a, b, st)$ and $xp(p, a, b, st)$ constituting numbers of st-th type vehicles performing freight and passenger transport tasks on p-th paths in relations (a, b). Then the criteria function:

$$\forall s \in \boldsymbol{S} \quad \sum_{st\in \boldsymbol{ST}} \sum_{(i,i')\in \boldsymbol{LE}} \sum_{(a,b)\in \boldsymbol{E}} \sum_{p\in \boldsymbol{P}_{ii'}^{ab}} [xt(p,a,b,st) + xp(p,a,b,st)] \cdot$$
$$\cdot\, d(i,i') \cdot ema(s,st,i,i') \cdot \psi a(s,st,p,a,b) \longrightarrow \min \tag{1}$$

Feasible solutions must keep the following constrains: all transport demand must be satisfied, sustaining material and passenger flows (additivity of traffic streams), total number of means of transport used for task realization, not exceeding the number of disposed vehicles, capacity of transport links (sections) can't be exceeded, ability of selected means of transport to move on particular sections of network, area/section access restrictions according to pollution, acceptable levels of harmful compounds emission can't be exceeded, loading capacity and defined number of passengers per vehicle, not overpassing vertical and horizontal gauge, maximum density of traffic on particular sections of network.

4. Computer implementation model

4.1. The model of transport network of Poland

The fundamental part of the simulation model of PTS is transport network model. Accordingly, the implementation of the model takes into account actual course of roads and lines, as well as their basic technological characteristics. Additionally the above elements must be included into model of transport network:

- nodal points (i.e. cross-roads, road and rail stops and stations, loading points, terminals, points of infrastructure characteristics change) with determined turning directions,
- areas of special land use (i.e. regions, counties, municipalities, cities, housing estates; the places where material and passengers streams appear and disappear), and their position in relation to transport network,
- communication areas cumulating dispersed freight shippers or recipients, as well as residential areas for passenger transport. Areas are connected to the network by links stating node in which material and passenger streams appear and disappear,
- specific public transport systems.

Transport network sections implemented into model are described by: individual name and number, length, number of tracks or roads and lanes, traffic directions, speed limit, railway or road category, technical class of road, tonnage (capacity) limits, vertical and horizontal marking on the section, surroundings (e.g. the terrain around the road or rail track, noise barriers, gauges etc.), types and characteristics of vehicles allowed to move through the section, average speed, and wind direction (important in dispersion of pollutants), etc.

Traffic data are defined by average annual movement, conclusive hourly traffic intensity and average velocity. Additionally the generic structure of the movement, directional distribution of traffic, and periodic fluctuations in traffic are included.

Traffic data were obtained from General Traffic Measurement in 2010 embracing 17 247 km of national roads cyclically performed by General Directorate for National Roads and Motorways. Remaining data were gained from local government bodies.

Additionally the specific over-county public transport systems are implemented by defining communication lines, and timetables. Lines are ascribed to transport relations. Locations of bus stops, daily number and regularity of drives, and carriers are known.

Sub-model of railway network bases on data provided by PKP PLK – national railway infrastructure manager. The following railway nodal points are included: stations and stops, junctions, endpoints of sidings, holds, groups of rails, siding posts, border crossings, and handling points. The parameterization of railway network includes: categories, number of tracks, electrification, speed limit for passenger and freight movement, maximum permissible axle load of locomotive, railway car and the electric multiple units, rail width, line purpose (passenger/freight), train control systems, capacity of rail nodes and groups.

Parameterization of roads and railways sections of allows traffic distribution on the transport network of Poland according to technical constrains and time of movement, and estimating levels of pollutants emitted into the environment.

All transport nodes in the network are the beginnings and ends of network's sections.

Moreover they can reproduce:
- existing and planned intersection of national, regional and municipal roads,
- significant technical changes in the cross-sections of roads,
- places where surroundings change (e.g. suburban road turns into urban, etc.)
- places where other characteristics of the road change significantly,
- the origins and destinations of material and passenger flows.

Turning relation in nodal points indicates if the turn in the specified direction is allowed. In addition, they allow defining the time necessary for a specific manoeuvre by various means of transport. In this way, it is possible to estimate the full route overcome time, with regard to detention at intersections, waiting at bus stops, etc. Changing mode of transport is possible and can be freely performed in appropriate nodal points.

4.2. Characteristics of transport means

Due to the different environmental impact of different means of road transport, model of PTS takes into account not only the loading capacity and technical purpose, but also:
- type of engine and fuel, including: gasoline, diesel fuel, liquid propane-butane gas LPG, compressed natural gas CNG, or hybrid engines, RSP ={1, 2, 3, 4, 5},
- EURO emission standard, including EURO 0 to EURO 6, NEU = {0, 1, 2, 3, 4, 5, 6}.

The set of experiments revealed unit factors of emission of selected harmful compounds of exhaust gases. The research was carried out in real operating conditions (urban and of-town) with on-board equipment and on engine dyno (see [11, 12]). Emission functions let to set close to the actual levels of emissions of pollutants from road transport. Analysing anticipated changes in the vehicle stock with regard to scenarios of transport system development, and forecasts of future transport needs allows identifying expected impact of road transport on the environment. It is assumed that electric railway transport does not emit considerable pollution, and its negative impact on atmosphere results from fossil-fuel-based production of energy.

Model of PST is focused on the following harmful compounds: CO (s = 1), HC (s = 2), NO (s = 3), NO_2 (s = 4), PM (s = 5), CO_2 (s = 6). Listed pollutants are ascertained for different traffic conditions that are determined by type of road (railway) as a function of mean velocity, load and the time elapsed since the start of the engine.

4.3. Demand model in a model of pro-ecological transport system of Poland

The basic sources of data on the demand for passenger and freight transport are:
- publications of Polish Central Statistical Office and Eurostat about transport activities,
- results of the project: "Logistics system of Poland as a way to co-modality of transport in European Union (see [8, 9]),
- results of national General Traffic Measurement in 2005 and 2010,
- rail and bus timetables and statistics about non-routine services.

Passenger transport requires formalization and quantitative description of motivations and destinations of travels. Then appropriate OD matrixes for: commuting to work/school, tourism, business, and other, must be developed. Information on this subject will came from existing timetables of public transport for different modes of transport and statistical data on the use of private transport.

Freight transport in PTS is modelled by characteristic component of PTV VISUM, s.c. *private transport module*. Passenger transport is modelled by characteristic components of PTV VISUM, s.c. *private transport module* and *public transport module* (public bus and rail communication) [14]. A schematic representation of demand for freight and passenger transport is presented in Fig. 2.

Private passenger transport

- Cars, commuting to work/school
- Cars, business travelling
- Cars, other

Public passenger transport
Aircraft, trains (EC, IC), inter-regio trains (IR), regional trains (R), buses/coaches

- Public transport, commuting to work/school
- Public transport, business travelling
- Public transport, other

Private transport - Freight trains, High-tonnage trucks

- Products of agriculture, hunting, forestry, fishing and fisheries
- Coal and lignite, crude oil and natural gas
- Metal ores and other mining and quarrying products
- Food products, beverages and tobacco
- Textiles and clothing, leather and leather products
- Wood, products of wood and cork (excluding furniture), articles of straw, paper, paper products,
- Coke, briquettes and refined petroleum products
- Chemicals, chemical products, fibres, rubber, plastics, nuclear fuel
- Production of other non-metallic materials
- Metals, fabricated metal products (except machinery and equipment)
- Machinery, equipment, electrical and electronic equipment
- Transportation equipment
- Furniture and other finished products
- Recyclable materials, municipal waste

Fig. 2. Transport sub-systems and segments of demand in freight transport in simulation model of PST

4.4. Material and passenger flows distribution and the pollution emission

One of the tools used in PTV VISUM to estimate harmful emission is *HBEFA module*. It reproduces pollution from transport connections basing on flow distribution, structure of vehicles, and unit emission factors of CO_2, CO, HC, NO_x, PM_x. Module contains historical data from 1990 up to forecasts to 2035. Vehicles structure embraces light commercial trucks, mix-truck, trailers, arctic traces; motorcycles, passenger cars, public transport, tour couches of different capacities and engine types. Particular entities of vehicles types are characterized by the share in total flow and unit emission factors.

HBFA module was supplemented by functional dependences of expected unit emission gained through empirical experiments described in point 4.2. Detailed assumptions for exemplary experiment are gathered in Tab. 1, and exemplary results in Tab. 2 and Fig. 3. Using developed functions of emission and measured unit emissions of harmful compounds, as well as HBEFA module allowed for series of simulation experiments to estimate level of emission. Fig. 4 presents total amount of emitted pollutants like CO_2, CO, HC, PM, NOx calculated on a base of number of high-tonnage trucks designed to the tasks in consequence of material, and passenger flows distribution.

Tab. 1. Detailed assumptions of on-board measurements for Mercedes C200

Engine	Duration	Distance	Fuel consumption		Stops	Avr. velocity	Avr. acceler.
1.8 dm^3 /Pb	2111 s	30.163 km	3.193 dm^3	10.587 dm^3/100km	20.17%	51.439 km/h	0.00416 m/s^2

Tab. 2. Detailed results of on-board measurements

Pollutant	CO	HC	NO_x	kNO_x	CO_2	PM
Mass of the compound [g]	47.5671	1.0255	0.3016	0.2413	7619.5358	0
Road unit emission [g/km]	1.577	0.034	0.01	0.008	252.612	0

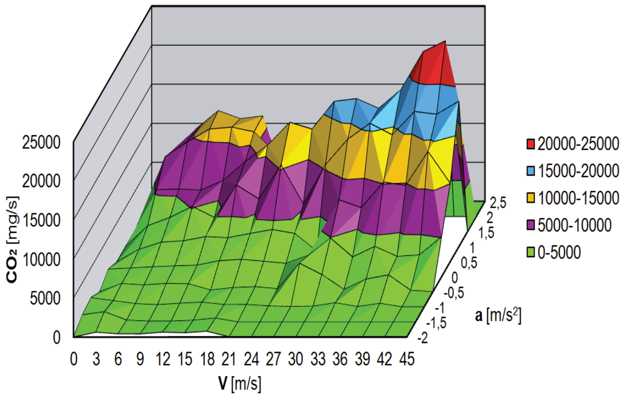

Fig. 3. CO2 emission in function of instantaneous velocity and acceleration

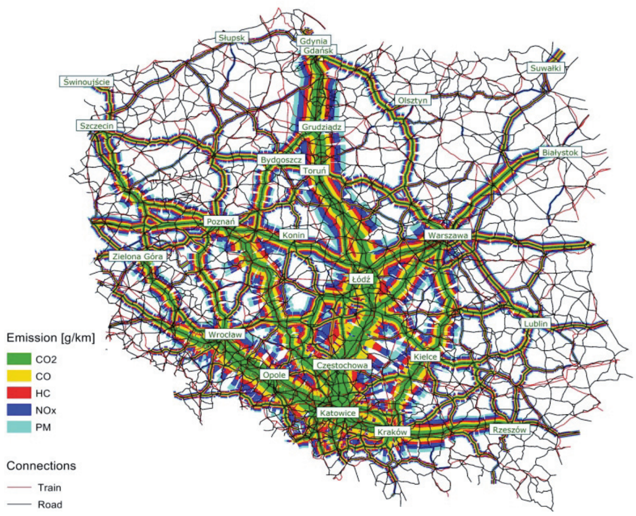

Fig. 4. Representation of pollutants emitted by freight transport in Poland

5. Conclusions

Developing a model of pro-ecological transport system will permit a wide range of research, experimentation and simulation of apportioning traffic streams on the transport network of the analysed area. It makes possible estimating the level of harmful emissions generated by the transport network users across the country or the particular areas.

Conducted experiments may involve changing parameters or adding new road or railway sections to the transport network, or changing demand segments, and then observing changes in emissions of harmful substances into the environment. Another advantage of model of PTS implementation is simulating changing the attractiveness of different modes of transport to the users, or restricting the use of network in the areas of special protection (near national parks, natural monuments, city centres, areas of Natura 2000, etc.), and analysing the distribution of environmental pollutants from the transport sector.

This will allow making studies and preparing proposals for amendments and modernization of the transport policy of the country. Gained results can be used as input data for models of pollution dispersion and circulation.

Acknowledgment

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

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