WARSAW UNIVERSITY OF TECHNOLOGY Index 351733
FACULTY OF CIVIL ENGINEERING
COMMITTEE FOR CIVIL AND WATER ENGINEERING
POLISH ACADEMY OF SCIENCES ISSN 1230-2945
DOI: 10.24425/ace.2020.131817
ARCHIVES OF CIVIL ENGINEERING
Vol. LXVI ISSUE 2 2020

A GENERALIZED METHOD FOR ASSESSING EMISSIONS FROM ROAD AND AIR TRANSPORT ON THE EXAMPLE OF WARSAW CHOPIN AIRPORT

MARIUSZ JACEK WASIAK[1], ADRIAN IOAN NICULESCU[2], MIROSŁAW KOWALSKI [3]

The article presents a method for assessing emissions of harmful substances and noise from road and air transport, as well as a combined assessment of the emissions of these transport pollutants. The original analytical dependencies reflecting the emissions of harmful substances from road transport, developed as part of the EMITRANSYS project implemented at the Faculty of Transport of the Warsaw University of Technology, were taken into consideration, in which the unit values of the actual road emissions of harmful substances are a function of, among other things, route length or speed of the vehicles. However, the dependencies associated with noise emissions were taken from the applicable international guidelines for assessing environmental pollution by traffic noise.

The article also describes a case study in which the impact of Warsaw Chopin Airport on noise along the Warsaw road network and the entire Warsaw agglomeration was assessed. Analyses and discussions were carried out in the scope of the change in transport noise due to air operations carried out in the analysed area. As agreed, the combined impact of road and aircraft noise in the area under study is far more unfavourable than street noise alone. Thus, it can be seen that the assessment of noise levels carried out separately for individual modes of transport (in accordance with applicable regulations) should be supplemented with the assessment of traffic noise from all modes of transport – especially in the case of simulation tests of ecologically friendly changes in the area of transport.

Keywords: road transport, air transport, noise emission, air pollution, external costs

[1] Faculty of Transport, Warsaw Uniwercity of Technology, Poland
[2] Department of Dynamic Systems, Institute of Solid Mechanics of the Rumanian Academy, Romania
[3] Air Force Institute of Technology in Warsaw, Poland

1. INTRODUCTION

The fact that transport is indispensable for the economy and social life is unquestionable, as is its adverse impact on the environment, both in terms of noise emissions, air pollution and other effects. As a consequence, decision-making models in the area of transport are increasingly being supplemented with environmental criteria (see e.g. [19, 21, 50]).

Street noise has been recognized by the World Health Organization as a serious public health problem, with road transport being responsible for the largest share of this emission [28]. Over 210 million people in the EU are exposed to harmful street noise which has various negative effects on human health. The impact of noise on health includes: disturbance of sleep, activity, performance and concentration, as well as irritation and stress, biological risk factors, cardiovascular diseases and mental disorders [5]. Noise also affects the environment by frightening and disorientating animals, as well as disrupting natural biological processes. Noise reduction, as well as reduction of exhaust emissions, is one of the basic trends towards cleaner, safer and more user-friendly transport in Europe. In contrast to street noise, aircraft noise is a special type of noise that covers large areas with its influence, and its impact is felt in areas around airports from various altitudes, without any possibility of silencing or shielding. The zones being the most threatened by aircraft noise are located in the immediate vicinity of the airport and in the zone of the air corridors of take-off and landing approach. In turn, the only methods of reducing the acoustic impact of air transport are planning and organizational activities in the form of special, anti-noise procedures for take-offs and landings.

In Poland, the permissible levels of traffic noise from road transport (per day L_{Aeq}) for the time of day have been determined as 61 dB in zones with single-family detached houses and 65 dB in zones with multi-family residential housing, while for night-time the permissible noise level for both of these zones was determined as 56 dB. However, for aircraft take-off and landing operations, the permissible noise levels in these zones are 60 dB during daytime and 50 dB for night-time [39].

Another important environmental impact of transport is the emission of air pollutants, which have a direct impact on human health, quality of life and the condition of the environment. On the scale of the European Union, transport is the source of almost 54% of the total nitrogen oxide emissions, 45% of carbon monoxide, 23% of non-methane volatile organic compounds, and 23% of PM10 dust and 28% of PM 2.5 dust (particulate matter with a diameter of 10 and 2.5 μm). Transport is also responsible for over 41% of tropospheric ozone precursor emissions as well as 23% of CO_2 emissions and almost 20% of other greenhouse gases [1].

Reducing the burden of transport on the environment is also particularly important due to the progressing global warming. Measures taken in this area include, among other things:

- implementation of alternative propulsion sources, including electric vehicles,
- energy recovery during braking,
- implementation of solutions in vehicles reducing air resistance (e.g. aerodynamic devices),
- impact on the modal division of transport (e.g. through transport policy, incentives and fiscal penalties, restrictions, creating ecologically friendly attitudes in society).

Due to the current state of the environment, simultaneous and multi-threaded comprehensive actions in various areas should be undertaken which lead to, among other things, reducing the negative impact of transport on the environment. It is crucial to assess the total impact of transport and measures undertaken in this area of influence on the environment.

The most appropriate approach to assessing the effects of ecologically friendly changes in transport seems to be simulation studies based on a mathematical modelling apparatus. Therefore, on the one hand, it requires the creation of multimodal transport models, and, on the other, the exploration and inclusion of considerations for functional dependencies in these models mirroring the impact of individual modes of transport on the natural environment, as well as allowing the assessment the overall impact of transport on the environment.

Considering the above, the article presents the results of research in the field of assessing the emissions of harmful substances and noise from road and air transport. These elements constitute an important part of the created model of a comprehensive assessment of the impact of transport on the natural environment, which – thanks to the combination with transport simulation models – will allow for assessing the impact of transport on the natural environment for various scenarios and decision-making variants.

2. THE ASSESSMENT OF THE ENVIRONMENTAL IMPACT OF TRANSPORT AND INTERNALISATION OF EXTERNAL COSTS – THE STATE OF KNOWLEDGE

The negative impact of transport on the natural environment entails significant costs, both direct (appearing in the design, manufacture, operation and utilization of transport means and infrastructure) and indirect (accidents, noise, vibrations). Although the effects of this impact are difficult to estimate, such research is increasingly often carried out [25, 26, 41].

The issue of the impact of noise on the life of population is described by, among others, Badyda [1], Czech and others [4], Gągorowski [16], Fuks and others [15], Orczyk and Tomaszewski [34] and other authors [12], [40] and [46]. The conducted research concerns mainly the impact of noise on health, as well as the methods of measuring noise levels depending on road conditions, as well as the effects and identification of noise from air transport, including solutions in the field of forecasting, simulation and minimization of the noise emitted by aircraft.

The assessment of the health effects of street noise is most often carried out in monetary terms. It is difficult, because noise does not cause direct losses, but through indirect influence, it causes problems to spread over time. In practice, it is assumed, that the amount of money that people are willing to pay to avoid street noise is a good estimate of the loss of people's well-being (willingness of people to pay - WTP [5]). According to an estimate of the social costs of street noise above 55 dB (A) carried out in 2007 in the EU, these amount to at least EUR 38 (30-46) billion per year. In the case of rail transport, in turn, the estimated social costs associated with noise amount to around EUR 2.4 billion per year. These estimates are probably understated [5]. Another measurement of the social costs of street noise is based on the assessment of life duration adjusted by disability. This represents the total number of the years of life lost due to premature death, and years lived with reduced health, weighted by the severity of health impairment [33]. The real-life calculations for both of these methods are comparable.

In the areas of the European Union countries, the following calculation methods for road noise emissions are used, among others [16]:

- NMPB-Routes-96 – a French method previously recommended by the European Union for use by individual member countries as a temporary method. This method includes considerations for, among other things, determination of the sound power level for each source (vehicle) and search for sound propagation routes between each source and the receiving point (direct route, reflected and/or refracted route) [13, 14, 29].
- RLS 90 - a German model, which takes into account the method of point sources along with propagation, attenuation at the ground, shielding and reflection. The RLS 90 guidelines set specific technical standards and procedures for the prediction and calculation of road and car park noise [38].
- CoRTN - an English method involving the source model and the calculations of propagation, whereby the method of calculating the propagation, ground effect and shielding, is based on the perpendicular distances of the source from the road [49].

In the field of noise emissions from air transport, the ECAC.CEAC Doc 29 method has been indicated as an interim one in the European Union with considerations of the segmentation technique for modelling aircraft flight paths [29] described in the document [7]. However, the currently applicable methods of noise assessment (among others noise from road and air transport) were described in the

Community Directive [6]. Of course, many factors influence the actual noise emission [42]. The calculation of noise-related road transport costs requires a combination of the data on noise exposure and cost factors for different noise ranges. The aforementioned cost factors may be adopted e.g. according to the HEATCO (2006 – [2]) method. For example, the total costs of noise on German motorways (outside agglomerations) are EUR 250 million per year [28]. When dividing into different categories of vehicles using traffic data from the TREMOVE model [35], this corresponds to the unit costs in Table 1.

Table 1. Illustrative average noise costs for German motorways, €ct (2010) per vkm

Vehicle type	Unit cost
Car	0.15
Motorcycle	0.61
LCV	0.18
Bus	0.48
HGV <16 t	0.44
HGV> 16 t	0.61

Source: [28], page 52.

The issue of testing exhaust emissions from transport is, similarly to the above, multi-threaded. One of the significant problems in this area is the identification of real road emissions, which – according to the test results described in the literature – do not usually comply with the emission indicators of harmful compounds which result from the standard of exhaust emissions met by a vehicle. The discrepancy in this respect is more pronounced especially for the means of transport meeting more stringent exhaust emission standards. Research in this area has been conducted, among others, by J. Merkisz et al. [32]. On the other hand, the issues of air pollution emissions from air transport have been studied, among others, by M. Jeż [27], D. Pyza & P. Gołda [36, 37] and M. Kowalski [30].

The past few decades have seen a significant progress in the development of aviation technology. The aircrafts which entered service in 2010 had specific (per passenger-kilometre) fuel consumption lower by 70% compared to those 50 years ago [27]. Due to such progress, in 2010 aircrafts consumed 3.5 litres of aviation fuel per 100 passenger-kilometres, or even as little as 3 litres of aviation fuel per 100 passenger-kilometres (Airbus A380 and Boeing 787). In turn, nowadays, fuel consumption is only about 2.8 litres per 100 passenger-kilometres (Boeing 747).

As it follows from Fig. 1 an aircraft engine, which consumes 1 ton of aviation fuel, will emit 4.38 tons of exhaust gases, on average, containing: 3.15 tons of carbon dioxide, 1.22 tons of water vapour and 13 kg of products resulting from incomplete combustion, including: 11.11 kg of nitrogen oxides (85.71%), 926 g of sulphur dioxide (7.14%), 741 g of carbon monoxide (5.71%), 148 g of unburned hydrocarbons (1.14%) and 37 g of particulate matter and soot (0.29%) [8]. However, it should be borne in mind that in real conditions the emission of these pollutants is highly dependent on engine loading. Consequently, it is different for all phases of the cycle: take-off and landing, taxiing (TX - Taxi in and taxi out on average about 7% of thrust), approach (AP - Approach, about 30% of thrust), the run after landing (AP - Landing, less than 30% of thrust), take-off (TO – Take-Off, 100% of thrust), climb (CL - Climb, 85% of thrust).

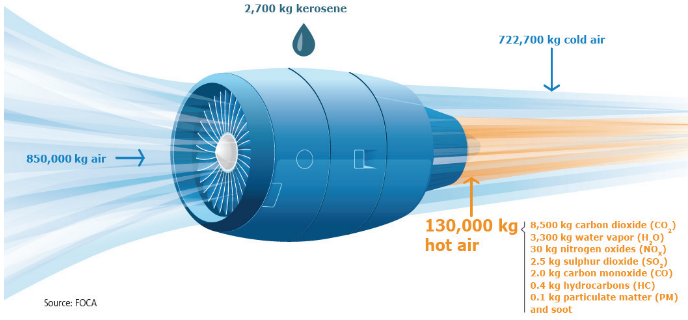

Fig. 1. Emissions from a typical two-engine jet aircraft during 1-hour flight with 150 passengers

Source: [8].

Ecological transport tests are carried out using specialised simulation tools, which, in most cases, are dedicated to conducting analysis in a strictly defined scope. For example, studies on the emissions of air pollutants from air transport, including their dispersion, are made possible by the following programs [27]:

- EDMS (Emissions and Dispersion Modelling System) - an American programme which allows for calculating the emissions from airports and air bases, taking into account all sources (access roads, car parks and local power plants) and their dispersion in the lower troposphere up to 1000 feet above the ground level.
- ALAQS (Airport Local Air Quality Studies) – a European programme with functionality similar to EDMS developed by the French ENVISA, commissioned by the EUROCONTROL Experimental Centre in Bretigny near Paris.
- ADMS-Airport (Atmospheric Dispersion Modelling System) - a British programme developed by Cambridge Environmental Research Consultants, constituting a tool for supporting air quality management in airport areas. It is an extension of the ADMS-Urban programme and enables simultaneous examination of 6.500 sources, including 500 jet aircraft and 1.500 road sources.

In the literature, one can also find models enabling the optimisation of aircraft flight trajectories with regard to the level of pollution and noise emissions [10, 11], as well as pro-ecological simulation models of urban transport [43] and in macro scale [20, 23, 25].

Table 2. Instruments for internalising the external costs of transport resulting from noise emissions and air pollution

Instrument name	Instrument type	Efficiency	Cost-efficiency ratio *
Transportation noise			
New braking systems of railway vehicles	Technical	High	1
Engine design changes	Technical	Low	2
Speed limits	Prescriptive-controlling	Average	3
Low noise tyres	Technical	Low	4
Sound-absorbing walls / soundproof screens	Infrastructure	High	5
Air pollution			
Buses and other vehicles with alternative propulsion (low and zero emissions)	Technical	Low	1
EURO emission standards	Prescriptive-controlling	High	2
Emission-related tolls Fuel tax	Economic	High	3
Urban parking policy (space availability, prices)	Economic / Infrastructure	Average	4
Tariff policy in urban public transport	Economic	Average	5
Urban traffic bans (low and zero emission zones)	Prescriptive-controlling	High	6
Speed limits	Prescriptive-controlling	Average	7
Climate changes			
Economical driving courses	Organizational / Institutional	Average	1
Kyoto mechanism (emissions trading, clean development mechanisms)	Economic	High	2
Fuel tax	Economic	High	3
Renewable energy sources for electricity production (railway, electric vehicles)	Technical	High	4
Buses and other vehicles with alternative propulsion (low and zero emission)	Technical	High	5
Imposing charges on vehicles with high CO_2 emissions or fuel consumption (i.e. low fuel efficiency) and discounts for vehicles with low CO_2 emissions or fuel consumption (i.e. high fuel efficiency).	Economic	Low	6
EURO exhaust emission standards and alternative fuels	Prescriptive-controlling	Average	7
Speed limits	Prescriptive-controlling	Average	8

* 1 - the measure with the highest cost-effectiveness ratio.
Source: the author's own elaboration based on [41].

The instruments for internalising indirect transport costs resulting from noise emissions and air pollution are presented in Table 2. They can be considered in terms of inter-branch and branch transport policy. The best example of an inter-branch policy instrument is the fuel (energy) tax. This charge is a particularly effective impact factor on the effects of climate change and energy efficiency, and indirectly contributes to the reduction of other consequences, e.g. noise, accidents, air pollution [22].

3. METHOD OF ASSESSING NOISE EMISSION AND AIR POLLUTION

In the light of previous considerations, the burden put by transport on the environment may be analysed from various points of view, with the important aspects of its assessment being the identification of noise emission and air pollution. In addition, in the environmental and social aspect, the assessment of a sustainable transport system includes – omitted in further considerations – external costs of transport regarding land occupancy, traffic congestion, collisions and transport accidents as well as water and soil pollution [3].

For the purpose of the model approach to the assessment of transport emissivity in terms of noise and environmental pollution, the following parameters were taken into account (cf. [24]):

$\boldsymbol{I}$ – a set of transport node numbers $\boldsymbol{I} = \{i: i = 1, ..., I\}$,

$\boldsymbol{K}$ – a set of transport subsystems numbers $\boldsymbol{K} = \{k : k = 1, 2\}$, with $k = 1$ being the passenger transport subsystem, and $k = 2$ - the freight transport subsystem,

$\boldsymbol{L}(r)$ – set of transport network sections for the r-th type of transport $\boldsymbol{L}(r) = \{(i, j): \zeta((i, j), r) = 1, i, j \in \boldsymbol{I}\boldsymbol{:}\ i \neq j\}, r \in \boldsymbol{R}$,

$\boldsymbol{M}$ – set of numbers of engine types used in transport means $\boldsymbol{M} = \{m: m = 1, ..., M\}$,

$\boldsymbol{M}(r)$ – a set of numbers of engine types used in transport means of the r-th type $\boldsymbol{M}(r) = \{m: \zeta 2(m, r) = 1, m \in \boldsymbol{M}\}, r \in \boldsymbol{R}$,

$\boldsymbol{N}$ – a set of numbers of exhaust emission standards for means of transport $\boldsymbol{N} = \{n: n = 1, ..., N\}$,

$\boldsymbol{N}(r)$ – a set of numbers of exhaust emission standards for means of transport of the r-th type $\boldsymbol{N}(r) = \{n: \zeta 3\ (n, r) = 1, n \in \boldsymbol{N}\}, r \in \boldsymbol{R}$,

$\boldsymbol{O}$ – a set of termination period numbers $\boldsymbol{O} = \{o: o = 1, ..., O\}$,

$\boldsymbol{P}(a, b)$ – a set of travel route numbers distinguished in the relation (a, b), $\boldsymbol{P}(a, b) = \{p: p = 1, ..., P(a, b)\}$,

$\boldsymbol{R}$ – a set of transport type numbers $\boldsymbol{R} = \{r: r = 1, ..., R\}$,

$\boldsymbol{S}$ – a set of numbers of harmful exhaust compounds emitted in connection with the traffic of transport means $\boldsymbol{S} = \{s: s = 1, ..., S\}$,

$\boldsymbol{T}(r, k)$ – a set of numbers of transport means types operated as part of the r-th type of transport and k-th transport subsystem $\boldsymbol{T}(r, k) = \{t: \zeta 1\ (t, r, k) = 1, t \in \boldsymbol{T}\}$, $r \in \boldsymbol{R}, k \in \boldsymbol{K}$,

$\boldsymbol{T}$ – a set of numbers of transport means types (in the case of road transport: light, motor vehicles (up to 3.5 t), medium heavy goods vehicles (two-axle) as well as heavy goods vehicles and two-wheel motor vehicles) $\boldsymbol{T} = \{t\colon t = 1, .. ., T\}$,

$\boldsymbol{Z}$ – a set of transport relations $\boldsymbol{Z} = \{(a, b)\colon a, b \in \boldsymbol{I}\}$,

d – distance between people exposed to noise and road axis [m],

$e_{k,i,j}^{r,t,m,n,s}$ – emission level of the s-th harmful exhaust compound during its operation on the (i, j)-th section of the transport network of the r-th type of transport of the t-th type, which is equipped with the t-th type of engine and meets the m-th standard of exhaust emissions and is a means of transport from the k-th transport subsystem [mg/s/veh], $r \in \boldsymbol{R}$, $k \in \boldsymbol{K}$, $(i, j) \in \boldsymbol{L}(r)$, $t \in \boldsymbol{T}(r, k)$, $m \in \boldsymbol{M}$, $n \in \boldsymbol{N}$, $s \in \boldsymbol{S}$,

$E_k^{s,o}$ – the amount of the emissions of the s-th harmful compound from the k-th transport subsystem in the o-th period [kg], $k \in \boldsymbol{K}$, $s \in \boldsymbol{S}$, $o \in \boldsymbol{O}$,

$f_{i,j}^r(\alpha_{i,j}^r, \phi 1_{i,j}^r, \phi 2_{i,j}^r, \pi)$ – noise reduction function for the (i, j)-th section of the transport network of the r-th type of transport limited by angle $\phi 1_{i,j}^r$ and the angle $\phi 2_{i,j}^r$ depending on the location of this section in relation to the observation point and the type of its shoulder $\alpha_{i,j}^r$ [dB], $r \in \boldsymbol{R}$, $(i, j) \in \boldsymbol{L}(r)$,

$l_{i,j}^r$ – the length of the (i, j)-th section of the transport network of the r-th mode of transport [km], $r \in \boldsymbol{R}$, $(i, j) \in \boldsymbol{L}(r)$,

$LeqH_{i,j}^{r,o}(d)$ – dependent on the distance d function of sound intensity emitted by means of transport loading in o-th period the (i, j)-th section of the transport network of the r-th type of transport [dB], $r \in \boldsymbol{R}$, $(i, j) \in \boldsymbol{L}(r)$, $o \in \boldsymbol{O}$,

$LeqH_{k,i,j}^{r,t,o}(d)$ – dependent on the distance d function of the sound intensity emitted by the means of transport of the t-th type operated in the k-th transport subsystem loading in o-th period (i, j)-th section of the transport network of the r-th type of transport [dB], $r \in \boldsymbol{R}$, $k \in \boldsymbol{K}$, $(i, j) \in \boldsymbol{L}(r)$, $t \in \boldsymbol{T}(r, k)$, $o \in \boldsymbol{O}$,

$u_{k,i,j}^{r,t,(a,b),p,m,n,o}$ – the share of the transport means of the t-th type equipped with engines of the m-th type and meeting the n-th emission standard in the loading of the (i, j)-th section of the transport network of the r-th type of transport with a flow of transport means of the t-th type operated in the k-th transport subsystem, which in the o-th period performed transport in the relation (a, b) along the p-th road [%], $r \in \boldsymbol{R}$, $k \in \boldsymbol{K}$, $(i, j) \in \boldsymbol{L}(r)$, $t \in \boldsymbol{T}(r, k)$, $(a, b) \in \boldsymbol{Z}$, $p \in \boldsymbol{P}(a, b)$, $m \in \boldsymbol{M}(r)$, $n \in \boldsymbol{N}(r)$, $o \in \boldsymbol{O}$,

$v_{k,i,j}^{r,t,o}(\mathbf{X}(i, j))$ – the speed along the (i, j)-th section of the transport network of the r-th type of transport for transport means t operated in the k-th transport subsystem at its loading in the o-th period $\mathbf{X}(i, j)$-th traffic flow [km / h], $r \in \boldsymbol{R}$, $k \in \boldsymbol{K}$, $(i, j) \in \boldsymbol{L}(r)$, $t \in \boldsymbol{T}(r, k)$, $o \in \boldsymbol{O}$,

$x_{k,i,j}^{r,t,o}$ – the loading of the (i, j)-th section of the transport network of the r-th type of transport with the flow of transport means traffic of the t-th type operated in the k-th transport subsystem in the o-th period [veh / h], $r \in \boldsymbol{R}$, $k \in \boldsymbol{K}$, $(i, j) \in \boldsymbol{L}(r)$, $t \in \boldsymbol{T}(r, k)$, $o \in \boldsymbol{O}$,

$x_{k,i,j}^{r,t,(a,b),p,o}$ – loading of the (i, j)-th section of the transport network of the r-th type of transport with a flow of traffic of the t-th type of transport means operated in the k-th transport subsystem, which in the o-th period performed transport in the relation (a, b) p-th way [veh / h], $r \in \boldsymbol{R}$, $k \in \boldsymbol{K}$, $(i, j) \in \boldsymbol{L}(r)$, $t \in \boldsymbol{T}(r, k)$, $(a, b) \in \boldsymbol{Z}$, $p \in \boldsymbol{P}(a, b)$, $o \in \boldsymbol{O}$,

$\alpha_{i,j}^{r}$ – noise emission factor depending on the road environment, including the presence of soundproof screens and other facilities, and roadside development for the (i, j)-th section of the transport network of the r-th type of transport [-], $r \in \boldsymbol{R}$, $(i, j) \in \boldsymbol{L}(y)$,

$\beta_{k}^{r,t}$, $\gamma_{k}^{r,t}$ – parameters of the average noise emission level for the transport means of the t-th type operated in the k-th transport subsystem of the r-th type of transport [-], $r \in \boldsymbol{R}$, $k \in \boldsymbol{K}$, $t \in \boldsymbol{T}(r, k)$,

$L_{k,i,j}^{r,t,o}(d)$ – sound intensity level of a transport vehicle of the-th type operated in the k-th transport subsystem, which in the o-th period loads the (i, j)-th section of the transport network of the r-th mode of transport [dB], $r \in \boldsymbol{R}$, $k \in \boldsymbol{K}$, $(i, j) \in \boldsymbol{L}(r)$, $t \in \boldsymbol{T}(r, k)$, $o \in \boldsymbol{O}$,

$L_{k,i,j}^{r,t,o}$ – sound power level of a transport vehicle of the t-th type operated in the k-th transport subsystem, which in the o-th period loads the (i, j)-th section of the transport network of the r-th mode of transport [dB], $r \in \boldsymbol{R}$, $k \in \boldsymbol{K}$, $(i, j) \in \boldsymbol{L}(r)$, $t \in \boldsymbol{T}(r, k)$, $o \in \boldsymbol{O}$,

$G_{i,j}^{r}$ – the directional coefficient of the (i, j)-th section of the transport network of the r-th mode of transport equalling: 1, when there are no sound reflecting surfaces, 2, when there is one sound reflecting surface, 4, when there are two sound reflecting surfaces, and 9, when there are three reflecting surfaces [-], $r \in \boldsymbol{R}$, $(i, j) \in \boldsymbol{L}(r)$,

$\psi_{k}^{r,t,(a,b),p,m,n,s}$ – for the p-th road in the relation (a, b) the indicator of the impact of the route length on the emission of the s-th harmful exhaust compound from the means of transport of the *t*-th type, equipped with the *m*-th type of engine and meeting the *n*-th standard of exhaust emissions operated in the *k*-th transport subsystem within the *r*-th mode of transport [-], $r \in \boldsymbol{R}$, $k \in \boldsymbol{K}$, $t \in \boldsymbol{T}(r, k)$, $(a, b) \in \boldsymbol{Z}$, $p \in \boldsymbol{P}(a, b)$, $m \in \boldsymbol{M}(r)$, $n \in \boldsymbol{N}(r)$, $s \in \boldsymbol{S}$.

The external costs of noise emissions are directly linked to noise levels and the number of people exposed to noise and their sensitivity to this factor. According to the results of the research, the percentage of people irritated by noise is strongly dependent on its level. It should also be noted that the very problem of estimating traffic noise is extremely complex and requires considering many factors.

In very simple terms, for any directional source of noise (e.g. a road vehicle, aircraft) moving at a certain speed in an open space, the sound intensity level can be calculated according to the following formula:

$$\forall o \in \boldsymbol{O} \quad \forall r \in \boldsymbol{R} \quad \forall k \in \boldsymbol{K} \quad \forall t \in \boldsymbol{T}(r,k) \quad \forall (i,j) \in \boldsymbol{L}(r)$$
$$L_{k,i,j}^{r,t,o}(d) = L_{k,i,j}^{r,t,o} + 10 \cdot \log \frac{G_{i,j}^{r}}{4\pi \cdot d^2} \qquad \text{(dB)} \tag{1}$$

In road transport, traffic noise depends primarily on: traffic volume, type of traffic structure, speed of traffic flow, distance from the road, sound-absorbing and sound-reflecting barriers, as well as the angle at which the observation is carried out. Taking into account these aspects, the sound intensity of a given type of vehicle can be determined according to the following dependency (FHWA model [47]):

$$\forall o \in \boldsymbol{O} \quad \forall r \in \boldsymbol{R} \quad \forall k \in \boldsymbol{K} \quad \forall t \in \boldsymbol{T}(r,k) \quad \forall (i,j) \in \boldsymbol{L}(r)$$
$$LeqH_{k,i,j}^{r,t,o}(d) = \beta_k^{r,t} \cdot \log\left(v_{k,i,j}^{r,t,o}(\mathbf{X}(i,j))\right) + \gamma_k^{r,t} + 10 \cdot \log\left(\frac{15 \cdot x_{k,i,j}^{r,t,o}}{v_{k,i,j}^{r,t,o}(\mathbf{X}(i,j))}\right) + \tag{2}$$
$$+ 10 \cdot \log\left(\frac{15}{d}\right)^{1+\alpha_{i,j}^{r}} + f_{i,j}^{r}\left(\alpha_{i,j}^{r}, \phi 1_{i,j}^{r}, \phi 2_{i,j}^{r}, \pi\right) - 25 \qquad \text{(dB)}$$

whereas:

$$\forall r \in \boldsymbol{R} \quad \forall (i,j) \in \boldsymbol{L}(r)$$
$$f_{i,j}^{r}\left(\alpha_{i,j}^{r}, \phi 1_{i,j}^{r}, \phi 2_{i,j}^{r}, \pi\right) = \begin{cases} 10 \log\left(\dfrac{\Delta \phi_{i,j}^{r}}{\pi}\right) & \text{gdy } \alpha_{i,j}^{r} = 0 \\ \left(10 \log \displaystyle\int_{\phi 1_{i,j}^{r}}^{\phi 2_{i,j}^{r}} \sqrt{\cos \phi} \; d\phi\right) - 10 \log \pi & \text{gdy } \alpha_{i,j}^{r} = \dfrac{1}{2} \end{cases} \qquad \text{(dB)} \tag{3}$$

Then, the total noise intensity along the sections of the transport network is calculated as follows:

$$\forall_{o \in \boldsymbol{O}} \ \forall_{r \in \boldsymbol{R}} \ \forall_{(i,j) \in \boldsymbol{L}(r)} \quad LeqH_{i,j}^{r,o}(d) = 10 \cdot \log\left(\sum_{k \in \boldsymbol{K}} \sum_{t \in \boldsymbol{T}(r,k)} 10^{\frac{1}{10} \cdot LeqH_{k,i,j}^{r,t,o}(d)}\right) \quad \text{(dB)} \tag{4}$$

In addition, it is important to remember to include in the analysis both traffic directions. The total noise emission from a section of the transport network taking into account both directions of movement is determined according to the formula:

$$\forall_{o \in \boldsymbol{O}} \ \forall_{r \in \boldsymbol{R}} \ \forall_{(i,j) \in \boldsymbol{L}(r)} \quad LeqH_{i,j}^{r,o}(d)^{*} = 10 \cdot \log\left(10^{\frac{1}{10} \cdot LeqH_{i,j}^{r,o}(d)} + 10^{\frac{1}{10} \cdot LeqH_{j,i}^{r,o}(d)}\right) \quad \text{(dB)} \tag{5}$$

Using an analogous dependency, noise levels from means of transport of various types should also be aggregated, but it is no less crucial to consider the relative location of the movement routes for the means of transport of different types.

The issue of the propagation of the noise emitted from air transport is much more complex. In this case, the types of transport modes and their parameters are also important. The individual phases of air operations, however, (taxiing, landing, etc.) are extremely important here[4]. The measure of the permissible level of aviation noise for take-offs, flights and landings is the value of long-term average sound level A(L_A) during six-month period which is the least acoustically favourable [39]. However, the nuisance of aircraft noise for a single aviation operation carried out at night-time is assessed through the sound exposure level A (L_{AE}). In this approach, appropriate modelling of the aircraft noise requires the construction of separate simulation models, which take into account the types of aircrafts, which serve a given airport and their most frequently followed movement trajectories during real air operations. The effect of such research is a map of exposure to the noise from air operations carried out at a given airport. Only then is it possible to aggregate the street and aircraft noise for the immediate vicinity of the road network and thus obtain a comprehensive assessment of the traffic noise, followed by external costs resulting therefrom.

The second negative impact of transport on the environment, considered in the article, is the emission of harmful exhaust compounds. However, when examining the problem in an overall approach, it is

[4] Description of the procedure for identifying noise pollution, e.g. in relation to air transport, together with a database containing the ecological characteristics of aircraft is an element of the Community Directive [6].

necessary to recognise not only the linear emissions generated as a result of vehicle movement, but also the point emission resulting from the production of energy used to propel transport means.

The level of the linear emission of harmful exhaust compounds depends on the speed of vehicle movement dependant on the volume of traffic, or the type of vehicle and its engine, including the exhaust emission standard being met. Moreover, accounting for the dependence of the emission of harmful emissions based on the distance of a given transport route (the shortest trips generate the highest emission), the pollutant emissions are defined below:

$$\forall o \in \boldsymbol{O} \quad \forall s \in \boldsymbol{S} \quad \forall k \in \boldsymbol{K}$$

$$E_k^{s,o} = 3600 \cdot 10^{-6} \cdot \sum_{r \in \boldsymbol{R}} \sum_{(i,j) \in \boldsymbol{L}(r)} \sum_{(a,b) \in \boldsymbol{Z}} \sum_{p \in \boldsymbol{P}(a,b)} \sum_{t \in \boldsymbol{T}(r,k)} x_{k,i,j}^{r,t,(a,b),p,o} \cdot \tag{6}$$

$$\cdot \sum_{m \in \boldsymbol{M}(r)} \sum_{n \in \boldsymbol{N}(r)} u_{k,i,j}^{r,t,(a,b),p,m,n,o} \cdot \frac{l_{i,j}^{r} \cdot e_{k,i,j}^{r,t,m,n,s}}{v_{k,i,j}^{r,t,o}(\mathbf{X}(i,j))} \cdot \psi_k^{r,t,(a,b),p,m,n,s} \qquad (\mathrm{kg})$$

The above relationship takes into account only the linear emission of air pollutants from internal combustion engines. It should be noted, therefore, that in this approach, the adverse impact of the so-called zero-emission vehicles, using electricity for propulsion, on the air is disregarded. Due to the still insignificant share of such vehicles in road traffic, this simplification can still be considered acceptable, nevertheless, in the case of a comprehensive assessment of the environmental impact of such vehicles, it is necessary to take into account, amongst others, point emissions of pollutants resulting from the production of electricity. These, in turn, are strongly conditioned by the structure of energy sources.

However, when referring to air pollution emissions from air transport, they can be assessed from the point of view of both the impact of this type of transport on climate change (high-altitude emissions), as well as its impact on the air quality around airports. For these purposes, a suitably modified form of dependence (6) and emissivity indicators depending on the types of aircraft, their number and load, as well as implemented phases of air operations (engine load) can be used.

4. CASE STUDY

4.1. THE CHARACTERISTICS OF THE STUDIED AREA AND ITS AIRPORT

To illustrate the impact of road and air transport on noise, calculations were carried out using the traffic model for the Warsaw agglomeration and the proposed method for the Warsaw Chopin Airport area, as well as for the rest of the Warsaw agglomeration. For the purposes of these analyses, layers of noise emissions from air traffic were superimposed on the traffic model. In addition, due to the scope of this model, the analysis was performed only for one hour of the morning rush hours, covering the time interval 07.00-08.00 The traffic load at this time, broken down by vehicle categories, is shown in Figure 2.

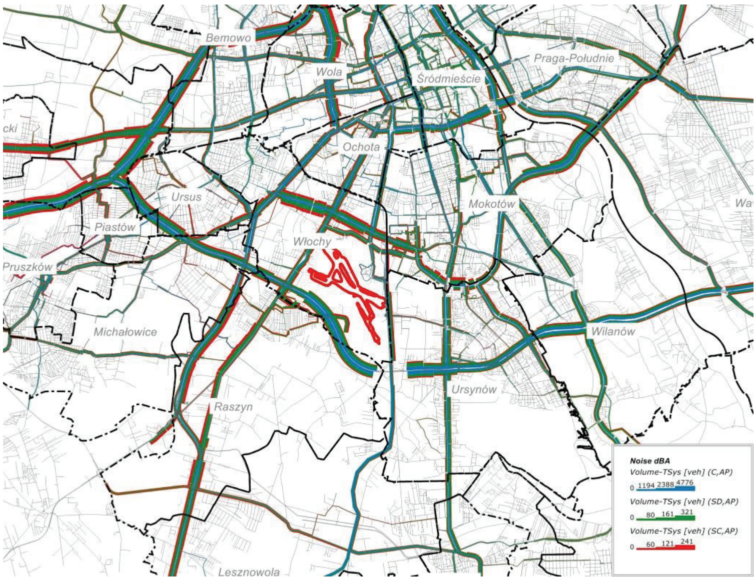

Fig. 2. The distribution of the traffic flow in the immediate vicinity of Warsaw Chopin Airport during the morning rush hour in 2017.

Source: the author's own elaboration based on the traffic model for the Warsaw agglomeration (Warsaw Traffic Study 2015 along with the traffic model, updated in July 2017).

In Figure 2, the zone of the greatest acoustic impact of Warsaw Chopin Airport is also marked in red, with its shape stemming the cross-shaped layout of the runways for take-off and landing.

As a number of documents demonstrate, Warsaw Chopin Airport, both during daytime and night-time, affects acoustically a considerable area. The extent of its significant influence includes 8 districts of Warsaw (Włochy, Ursus, Ursynów, Mokotów, Wilanów, Ochota, Wola and Bemowo) and 9 Warsaw suburban communes (Michałowice, Raszyn, Lesznowola, Piaseczno, Piastów, Pruszków, Ożarów Mazowiecki, Stare Babice and Konstancin Jeziorna). Resolution No. 76/11 of Mazovian Voivodeship Local Assembly (Sejmik) of 20 June 2011 and Resolution No. 153/11 on 24 October 2011 specified the range of the limited use area for the Warsaw Chopin Airport, in which two zones (Z1 and Z2) being constantly exposed to significant aircraft noise were distinguished (Fig. 3). The outer boundary of the limited use area is the envelope of the isoline of the equivalent level of sound A L_{AeqN} = 45 dB and the isoline L_{AeqD} = 55 dB if the isoline L_{AeqN} = 45 dB is inside the area limited by the isoline L_{AeqD} = 55 dB. Whereas the Z1 zone covers areas where the night-time noise level exceeds 55 dB, while the Z2 zone covers the area where the night-time noise level is contained in the range of 50-55 dB [48]. The limited use area covering the total of 105.85 km^2 is inhabited by approximately 317 thousand people, of whom approximately 970 people live within the Z1 zone with an area of 3.23 km^2.

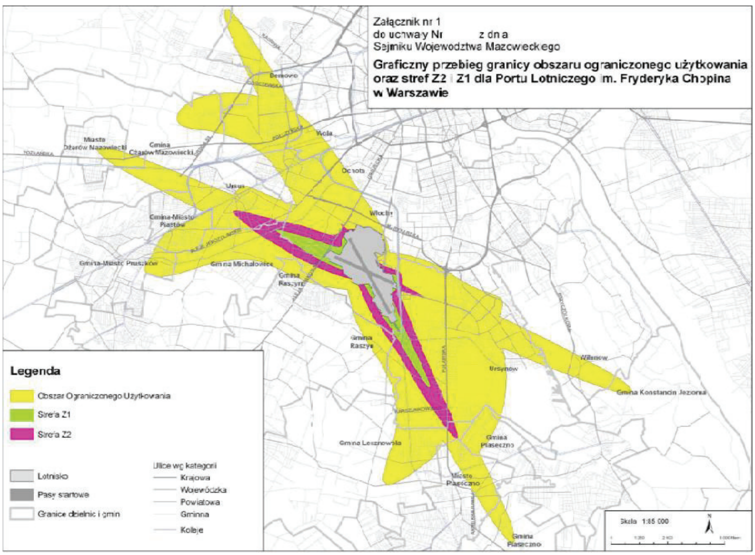

Fig. 3. Limited use area for Warsaw Chopin Airport

Source: [48].

At Chopin Airport, take-off and landing operations in 2016 were performed by nearly 200 types of aircraft, where the types of aircraft operating most frequently at this airport in 2016 were [30]:

- Embraer 175 (15.13% of operations),
- Airbus 320 (13.56% of operations),
- Embraer 195 (8.49% of operations),
- Embraer 170 (7.25% of operations),
- Boeing 738 (6.55% of operations).

4.2. NOISE EMISSIONS FROM ROAD AND AIR TRANSPORT

Firstly, calculations were made in the scope of estimating street noise during the morning rush hour, which results from the traffic model for the Warsaw agglomeration. These calculations were carried out for a distance from the road axis equal to 5, 10 or 15 m. The result of these analyses carried out in accordance with the previously described model is shown in Fig. 4 and in Table 3, while the Fig. 5 and Table 3 contains the results of assessing the impact of aircraft noise on noise emissions along the roads of the Warsaw agglomeration.

Fig. 4. The emission of road noise in the immediate vicinity of Warsaw Chopin Airport during the morning rush hour in 2017.

Source: the author's own elaboration based on the traffic model for the Warsaw agglomeration (Warsaw Traffic Study 2015 along with the traffic model, updated in July 2017).

The table summarizes the data regarding the length of the road sections of the entire Warsaw agglomeration by noise level at the distance of 5, 10 and 15 meters, with considerations for only road noise and with considerations for aircraft noise. This table also contains similar data only for the Warsaw transport network.

Fig. 5. The emission of road noise and aircraft noise in the immediate vicinity of Warsaw Chopin Airport during the morning rush hour in 2017.

Source: the author's own elaboration based on the traffic model for the Warsaw agglomeration (Warsaw Traffic Study 2015 along with the traffic model, updated in July 2017).

As can be inferred from the research conducted air transport causes a significant increase in noise pollution along the road network. For a distance of 5 m from the road axis in the studied area, due to air traffic there occurs as high as 31% increase in the length of sections with the noise level between 50 and 55 dB, a 6% increase in the length of sections with a noise level between 55 and 60 dB and 3.3 % increase in the length of sections with a noise level between 60 and 65 dB. For larger distances from the road axis, the impact of air traffic on noise along roads varies depending on the area under study. In the case of Warsaw and the distance from the road axis of 10 m there was a 3.7% increase in the length of sections with a noise level between 50 and 55 dB, a 12.8% increase in the length of sections with a noise level between 55 and 60 dB and a 7.5% increase in length of sections with a noise level between 60 and 65 dB. However, for a distance from the road axis of 15 m in this area, a 4.7% increase in the length of the sections with a noise level between 50 and 55 dB was noted, a 17.7% increase in the length of the sections with a noise level between 55 and 60 dB, and an 8.2% increase in the length of the sections with a noise level between 60 and 65 dB. The increase in the length of the road sections with a noise level between 70 and 75 dB is also quite significant (equal to 1.1%).

Table 3. The assessment of the impact of aviation noise on environmental noise pollution along the road network of the Warsaw agglomeration

The level of traffic noise	Road noise			Road and aircraft noise			Change of noise along roads due to aircraft noise		
	Distance from road axis								
	5m	10m	15m	5m	10m	15m	5m	10m	15m
Warsaw Agglomeration									
up to 45 dB	1 679.9	4 654.8	4 778.6	1 602.8	4 462.5	4 625.9	-4.6%	-4.1%	-3.2%
from 46 to 50 dB	2 994.8	237.4	436.5	2 936.2	271.4	406.8	-2.0%	14.3%	-6.8%
from 51 to 55 dB	233.5	874.3	1 169.7	307.4	936.2	1 233.6	31.6%	7.1%	5.5%
from 56 to 60 dB	941.2	1 076.1	938.3	997.6	1 168.5	1 054.8	6.0%	8.6%	12.4%
from 61 to 65 dB	1 083.7	855.6	728.7	1 119.9	895.6	765.6	3.3%	4.7%	5.1%
from 66 to 70 dB	831.2	640.6	596.1	841.0	643.2	598.7	1.2%	0.4%	0.4%
from 71 to 75 dB	627.1	574.6	503.1	627.1	576.6	506.5	0.0%	0.3%	0.7%
above 75 dB	840.5	318.5	81.1	841.0	318.9	81.1	0.1%	0.1%	0.0%
Warsaw									
up to 45 dB	1 410.3	1 597.5	1 683.6	1 334.7	1 511.4	1 589.3	-5.4%	-5.4%	-5.6%
from 46 to 50 dB	201.2	147.2	332.8	190.4	132.6	302.7	-5.4%	-9.9%	-9.0%
from 51 to 55 dB	144.4	683.8	725.1	189.4	709.2	759.0	31.2%	3.7%	4.7%
from 56 to 60 dB	739.9	604.3	521.8	775.6	681.7	614.3	4.8%	12.8%	17.7%
from 61 to 65 dB	580.6	408.3	370.2	615.6	439.0	400.5	6.0%	7.5%	8.2%
from 66 to 70 dB	398.4	335.4	326.3	406.3	337.7	328.0	2.0%	0.7%	0.5%
from 71 to 75 dB	331.5	358.8	322.4	331.5	360.7	325.8	0.0%	0.5%	1.1%
above 75 dB	495.2	166.3	19.5	495.7	166.7	19.5	0.1%	0.3%	0.0%

Source: the author's own elaboration based on the traffic model for the Warsaw agglomeration (Warsaw Traffic Study 2015 along with the traffic model, updated in July 2017)

5. CONCLUSIONS

Due to the observation of increasingly more pronounced adverse changes of climate and the quality of human life, the research on the impact of road transport on the environment, leading to the reduction of adverse impacts, is gaining increasing importance. Among other things, the specificity of individual modes of transport results in the high complexity and multi-faceted nature of this issue. For example, the assessment of the impact of road transport involves issues of road emission testing, and the assessment of the impact of air transport requires mapping the trajectory of aircraft movement and their flight parameters. Studying individual issues is a separate scientific challenge (see e.g. [9], [17], [18], [44], [45], [51]). Also, of particular importance are studies leading to obtaining multimodal simulation transport models enabling (to a varying extent) the assessment of the impact of transport operations on the environment.

The model described in the article makes it possible to assess the combined impact of road and air transport on the environment in terms of noise emissions and air pollution. In particular, the presented analytical relationships enable the assessment of noise emissions and air pollution from road transport, taking into account the intensity of traffic as well as other parameters of vehicle traffic and their structure per type. Thus, this model can be used to assess the impact of changes in the distribution of traffic flows, or the structure of vehicles per type on the level of transport impacts imposed on the environment analysed in the article. Therefore – provided it is connected to the multimodal simulation transport model – it can be used to analyse the effectiveness of the so-called pro-ecological changes in the transport system (e.g. introduction of zero-emission zones).

In addition, the presented approach allows and justifies an overall assessment of the environmental impact of different transport modes. Overlapping acoustic impacts of different modes of transport may lead to noise levels which are much more onerous for humans and animals than the noise levels identified separately for each type of transport. These relationships are shown in the case study analysed in the article. Therefore, the assessment of noise levels carried out separately for individual modes of transport should be supplemented with the assessment of the traffic noise produced by all modes of transport - especially in the case of simulation tests of pro-ecological changes in the area of transport.

REFERENCES

1. Badyda A.J., „Zagrożenia środowiskowe ze strony transportu", NAUKA, 2010; 4, 115-125.
2. Bickel P., Friedrich R., Burgess A., Fagiani P., Hunt A., De Jong G., Laird J., Lieb Ch., Lindberg G., Mackie P., Navrud S., Odgaard T., Ricci A., Shires J., Tavasszy L., Proposal for Harmonised Guidelines. Deliverable D5 of HEATCO Project, IER - University of Stuttgart, Stuttgart 2006.
3. CE Delft, Infras, Fraunhofer ISI. External Costs of Transport in Europe. Update Study for 2008 Delft, Delft 2011.
4. Czech P., Stanik Z., Warczek J., Witaszek K., Witaszek M., "Influence of general vibration at the passengers comfort in passengers cars", Traffic Injury Prevention. 2015, 4, 2845-2854.
5. den Boer E., Schroten A., Traffic noise reduction in Europe CE Report. Delft 2007.
6. Dyrektywa 2002/49/WE Parlamentu Europejskiego i Rady z dnia 25 czerwca 2002 r. odnosząca się do oceny i zarządzania poziomem hałasu w środowisku (wersja skonsolidowana z dnia 26.07.2019 r.).
7. ECAC.CEAC Doc 29, Report on Standard Method of Computing Noise Contours around Civil Airports, 4th Edition, 2016.
8. European Aviation Environmental Report 2019, EASA, EEA, EUROCONTROL.
9. Figlus T., Konieczny Ł., Burdzik R. , Czech P., "The effect of damage to the fuel injector on changes of the vibroactivity of the diesel engine during its starting", Vibroengineering Procedia. 2015, 6, 180-184.
10. Filippone A., "Multi-disciplinary simulation of propeller-turboprop aircraft flight", The Aeronautical Journal, 2012; 116 (1184), 985-1014.
11. Filippone A., Zhang M., Bojdo N., "Validation of an integrated simulation model for aircraft noise and engine emissions", Aerospace Science and Technology, 2019; 89, 370-381.
12. Filippone A., "Aircraft noise prediction", Progress in Aerospace Sciences, 2014; 68, 27-63.
13. French national computation method "NMPB-Routes-96 (SETRA-CERTU-LCPCCSTB)", referred to in Arrêté du 5 mai 1995 relatif au bruit des infrastructures routières, Journal Officiel du 10 mai 1995, Article 6.

14. French standard XP S 31-133:2001, Acoustique – Bruit des infrastructures de transports terrestres – Calcul de la attenuation du son lors de sa propagation en milieu extérieur, incluant les effets météorologiques, AFNOR, 2001.
15. Fuks K., Moebus S., Hertel S., Viehmann A., Nonnemacher M., Dragano N., Möhlenkamp S., Jakobs H., Kessler C., Erbel R., Hoffmann B., "Long-term urban particulate air pollution, traffic noise, and arterial blood pressure", Environmental health perspectives, 2011; 119 (12), 1706-1711.
16. Gągorowski A., „Badania hałasu drogowego z uwzględnieniem różnych metod obliczeniowych", Prace Naukowe Politechniki Warszawskiej. Transport, 2013; 89, 19-33.
17. Gołda P., Kowalski M., Wasser C., Dygnatowski P., Szporka A., "Elements of the modelpositioning of aircraft on the apron", Archives of Transport, 2019; 51 (3), 101-108.
18. Gołda P., "Selected decision problems in the implementation of airport operations", Scientific Journal of Silesian University of Technology. Series Transport, 2018; 101, 79-88.
19. Izdebski M., Jacyna M., "The organization of the municipal waste collection: the decision model", Annual Set The Environment Protection. 2018, 20, 919-933.
20. Jachimowski R., Kłodawski M., Lewczuk K., Szczepański E., Wasiak M. "Implementation of the model of proecological transport system", Journal of KONES, 2013; 20 (4), 129-139.
21. Jacyna M., Kłodawski M., „Model of transportation network development in aspect of transport comodality", Proceedings - ICSEng 2011: International Conference on Systems Engineering2011. 2011, 341-345.
22. Jacyna M., Wasiak M. "Multicriteria Decision Support in Designing Transport Systems", Mikulski, J. (ed). Tools of Transport Telematics, 2015; 531, 11-23. DOI.10.1007/978-3-319-24577-5_2
23. Jacyna M., Wasiak M., Lewczuk K., Chamier-Gliszczyński N., Dąbrowski T., "Decision problems in developing proecological transport system", Rocznik Ochrona Środowiska. Annual Set The Environment Protection, 2018; 20, 1007-1025.
24. Jacyna M., Wasiak M., Lewczuk K., Karoń G., "Noise and environmental pollution from transport: decisive problems in developing ecologically efficient transport systems", Journal of Vibroengineering. 2017; 19 (7). 5639-5655.
25. Jacyna M., Wasiak M., Lewczuk K., Kłodawski M., "Simulation model of transport system of Poland as a tool for developing sustainable transport", Archives of Transport, 2014; 31 (3), 23-35.
26. Jacyna-Gołda I., Gołębiowski P., Izdebski M., Kłodawski M., Jachimowski R., Szczepański E., „The evaluation of the sustainable transport system development with the scenario analyses procedure", Journal of Vibroengineering. 2017, 19 (7), 5627-5638.
27. Jeż M., „Ekologiczne problemy portu lotniczego", Prace Instytutu Lotnictwa, 2010; 4 (206), 59-71.
28. Korzhenevych A., Dehnen N., Bröcker J., Holtkamp M., Meier H., Gibson G., Varma A., Cox V., Update of the Handbook on External Costs of Transport. Final Report. Report for the European Commission: DG MOVE Ricardo-AEA/R/ED57769 Issue Number 1 8 th January 2014.
29. Kossakowski P., "Protection against noise in the European Union – general requirements, applied noise indicators and assessment methods", Structure and Environment, 2011; 3 (4), 38-41.
30. Kowalski M., "Noise emission level versus the structure of the aircraft turbine engine", Journal of KONES Powertrain and Transport, 2012; 19 (4), 325-332.
31. Mapa Akustyczna dla portu lotniczego im. F. Chopina w Warszawie, Warszawa 2017.
32. Merkisz J., Jacyna M., Merkisz-Guranowska A., Pielecha J., "The parameters of passenger cars engine in terms of real drive emission test", Archives of Transport, 2014, 32 (4), 43-50.
33. Monetisation of the health impact due to traffic noise. Swiss Agency for the Environment, Forests and Landscape, Bern 2003.
34. Orczyk M., Tomaszewski F., "Studies and assessment of transport noise in Poznan", Archives of Transport, 2016; 37 (1), 43-54.
35. Proost S., TREMOVE 2 Service contract for the further development and application of the TREMOVE transport model - Lot 3: Final Report Part 2: Description of the baseline. European Commission, Directorate General of the Environment, Brussels 2006.
36. Pyza D., Gołda P., "Cost of Environmental Pollution in Air Transport of Cargo Shipments", International Journal of Energy Science, 2012; 2 (3), 104-109.
37. Pyza D., Jacyna-Gołda I., Gołda P., Gołębiowski P., "Alternative fuels and their impact on reducing pollution of the natural environment", Rocznik Ochrona Środowiska. Annual Set The Environment Protection, 2018; 20 (1), 819-836.
38. Richtlinien für den Lärmschutz an Straßen. RLS-90. 1990.
39. Rozporządzenie Ministra Środowiska z dnia 14 czerwca 2007 r. w sprawie dopuszczalnych poziomów hałasu w środowisku, ze zm.
40. Sahaia A., Wefersb F., Pickc S., Stumpfa E., Vorländerb M., Kuhlen T., "Interactive simulation of aircraft noise in aural and visual virtual environments", Applied Acoustics, 2016; 101, 24-38.

41. Schreyer Ch., Schneider Ch., Maibach M., Rothengatter W., Doll C., Schmedding D., External costs of transport - Update study. Final Report. IWW Uniwersitaet Karlsruhe, INFRAS. Zurich/Karlsruhe 2004.
42. Sobota A., Żochowska R., Szczepański E., Gołda P., "The influence of tram tracks on car vehicle speed and noise emission at four-approach intersections located on multilane arteries in cities", Journal of Vibroengineering. 2018; 20 (6), 2453-2468.
43. Strulak-Wójcikiewicz R., Lemkea J., "Concept of a Simulation Model for Assessing the Sustainable Development of Urban Transport", Transportation Research Procedia, 2019; 39, 502-513.
44. Świderski A., Borucka A., Jacyna-Gołda I., Szczepański E., "Wear of brake system components in various operating conditions of vehicle in the transport company", Eksploatacja i Niezawodność – Maintenance and Reliability. 2019, 21 (1), 1-9.
45. Świderski A., Jóźwiak A., Jachimowski R., "Operational quality measures of vehicles applied for the transport services evaluation using artificial neural networks". Eksploatacja i Niezawodność – Maintenance and Reliability. 2018, 20 (2), 292–299.
46. Tomaszewski F., Misztal W., „Oddziaływanie hałasu lotniczego na środowisko", Czasopismo Techniczne. Mechanika, 2012; 14 (7-M/2012), r. 109, 307-316.
47. U.S. Department of Transportation. Fedral Highvay Administration. FHWA Highway Traffic Noise Prediction Model, 1978.
48. Uchwała nr 76/11 Sejmiku Województwa Mazowieckiego z dnia 20 czerwca 2011 r. w sprawie utworzenia obszaru ograniczonego użytkowania dla Portu Lotniczego im. Fryderyka Chopina w Warszawie
49. United Kingdom, Department of Transport, 1988 Calculation of Road Traffic Noise (UK DoT 1988 CORTN) noise prediction model.
50. Wasiak M., Jacyna M., Lewczuk K., Szczepański E., „The method for evaluation of efficiency of the concept of centrally managed distribution in cities", Transport. 2017, 32 (4), 348-357.
51. Zieja M., Golda P., Zokowski M., Majewski P., „Vibroacoustic technique for the fault diagnosis in a gear transmission of a military helicopter", Journal of Vibroengineering. 2017, 19 (2), 1039-1049.

LIST OF FIGURES AND TABLES:

Received 05.03.2020, Revised 28.05.2020