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Investigation of noise barriers enhancement efficiency for attenuation of low frequency traffic noise

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1. Introduction

Noise impact assessment plays a relevant role in the whole process of environmental impact assessment (EIA). In particular, various noise management-related difficulties occur when developing and implementing transport infrastructure projects. One of the most common and basic criteria for noise impact assessment in transport infrastructure projects and selecting noise abatement measures (including noise barriers) are the overall A-weighted rated sound levels. Meanwhile assessing low frequency noise (LFN) is a rather new procedure in transport infrastructure projects. Sometimes this procedure tends to be ignored even if a country has adopted certain legal requirements concerned with noise regulation at low frequencies. One of the reasons of this - noise calculation software and methods used by environmental assessment professionals in transport infrastructure projects are adapted for calculating merely the overall A-weighted sound levels. The range of frequencies that is considered a low frequency sound in different countries often depends on the legally defined limit levels of the sound. Generally, it is considered that low frequency sounds are those up to 200 - 250 Hz, the lowest frequency means often overlaps or overlays the infrasound range (below 20 Hz). Unlike usual environmental noise (overall A-weighted rated sound levels) which is normally regulated both indoors and outdoors of residential house, LFN limit values are defined only indoors. Furthermore, regulated LFN limit values differs up to 22 dB at some frequencies in different countries [1-3].

Road traffic noise and measures to reduce it are widely investigated from different point of view: starting with noise appearing in a source (tyre/road interaction e.g. [4-6], engine and exhaustion system noise e.g. [7, 8]) investigations, continuing with investigations of sound propagation and reduction measures (like noise screens (barriers), gabions, plants and other, e.g. [9-11]) and finishing with measures at receiver (window glazing and air venting, façade insulation, e.g. [12, 13]). There are many national and international road traffic noise calculation methods (within commercial software), which are based on empirical or ray tracing methods [14], with possible up to 15 dB(A) differences in outcome of noise calculations [15]. According [16], some of them are “relatively simple engineering methods based on A-weighted levels or on octave bands on one side” (e.g. RLS-90 (Richtlinien für den Lärmschutz an Strassen, Germany), CRTN (Calculation of Road Traffic Noise, UK), NMPB - Routes-96 (Nouvelle Methode de Prevision de Bruit, France) etc.) “and more complex methods with narrow frequency bands, coherent superposition of different contributions from the same source, inclusion of Fresnel-Zone weighting of reflected sound and of meteorological effects in some cases” (eg. NORD 2000 (Nordic noise prediction method), Harmonoise/Imagine (Improved Methods for the Assessment of the Generic Impact of Noise in the Environment) or SonRoad (Swiss noise prediction method)). These methods have they own equations for calculation of noise barrier sound reduction, many of them have corrections, based on the measurements performed by Maekawa [17, 18]. To simulate performance of more complex material and shape noise barriers in a certain interval of frequencies, numerical methods are more suitable comparing methods listed before. For road traffic noise simulation and noise measures (noise barriers) performance more often, parabolic equation method (e.g. [19, 20]) or boundary element methods are used (eg. [21, 22]). On the other hand, for solving complex acoustics tasks, finite element method (FEM) is widely used. FEM demands big computer resources, therefore is used to solve acoustic tasks in limited spaces.

This investigation was carried out in order to find out the spectrum of heavy duty traffic busy road and to make sure if existing noise barriers are efficient for attenuation of low frequency noise and what improvements could be made. It is based on actual measurements and calculations using FEM with COMSOL software.

2. Measurements of sound power level of traffic noise: Conditions and results

In order to identify a noise spectrum of busy road with a big percentage of lorries and to measure effectiveness of existing noise barriers at different frequencies noise measurements at free field conditions and behind existing noise barriers were made. Measurements of traffic noise and noise reduction of noise barriers have been made using 2 Brüel & Kjær sound level meters Type 2260 Investigator™; calibrator Brüel & Kjær 4231. Microphone height was 1.5 m. Air temperature was ~20°C and wind speed was < 5 m/s.

The noise measurements were executed near main road A5 Kaunas – Marijampole – Suwalki that is part of the transport corridor E67 Helsinki - Tallinn - Riga - Panevezys - Kaunas - Warsaw - Wroclaw – Prague where annual average traffic is 19264 veh./day (near Garliava) and 311914 veh./day (in Kaunas). The road has the biggest percentage of heavy vehicles traffic in Lithuania - respectively 49.8 and 43.3 percent [23, 24]. High amount of heavy vehicles indicates that traffic noise will consist of high levels of LFN.

For model verification, noise measurements have been carried out in free field conditions (500 m out from nearest noise barrier) in a distance of 3, 10 and 20 m from the nearest driving lane (or 6, 13, and 23 m from the nearest driving lane axis). For model suitability to calculate noise reduction of noise barriers, measurements have been carried out in a row with noise barriers (~3 m from the nearest driving lane) and right behind the barrier (4 m from barrier). To reduce the influence of lateral diffraction of sound waves, measurement positions were established in a distance of 40 m from the ending of noise barriers.

Measurements have been made 3 times (10 minutes each) at every point by calculating passing vehicles.

Properties of noise barrier No. 1: height – 3 m, material – wooden planks (2 cm thickness) (larch) and mineral wool inside (thickness 10 cm). Gaps between planks are 2 cm.

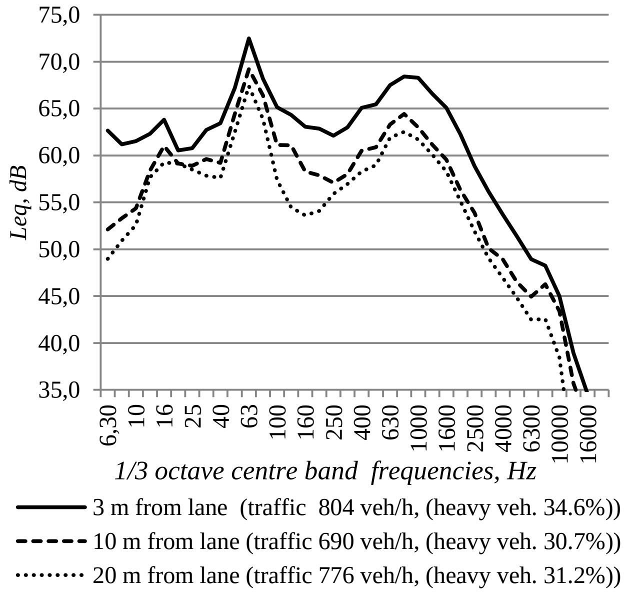

Fig. 1 Noise measurements results of the of unweighted equivalent sound pressure levels in free field conditions

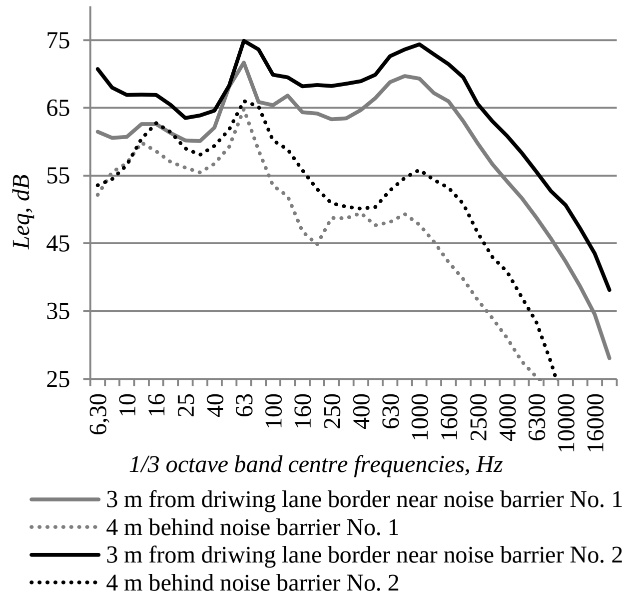

Fig. 2 Noise measurements results of unweighted equivalent sound pressure levels near and behind noise barriers

Steel struts are behind screen.

Properties of noise barrier No. 2: height – 3 m, material – plastic and mineral wool inside (width 10 cm). Planks are built in steel struts.

Results of the measurements are presented in the Figs. 1 and 2.

Traffic noise is not constant and depends on many factors such as traffic volume and content, speed of vehicle and individual properties of them. From measurements in free field conditions and near driving lane beside noise barriers (also in free field conditions), it is obvious that noise spectrum of the road has 2 peaks: at 63 Hz and 800-1600 Hz frequencies.

Considering measurement results near noise barriers, difference between $L_{Aeq(6.3Hz\text{-}20kHz)}$ at distance of 3 m from driving lane (in a row with barrier) and 4 m behind noise barrier No. 1 was 20.6 dB(A); respectively behind noise barrier No. 2 was 18.6 dB(A). Taking in to account only low frequencies the difference of $L_{eq(16\text{-}200Hz)}$ was respectively 13.7 dB and 11.7 dB. Measurements results at 1/3 octave centre band frequencies are provided in Table 1.

Table 1

Noise measurements results of unweighted equivalent sound pressure levels (L_{eq}) at noise barriers No. 1 and No. 2, dB

1/3 octave band centre frequencies, Hz	16	20	25	31.5	40	50	63	80	100	125	160	200
3 m from driving lane	62.6	61.3	60.2	60.1	62.1	68.1	71.7	65.9	65.4	66.8	64.4	64.1
4 m from noise barrier No. 1	58.6	57.0	56.2	55.5	56.7	59.2	64.8	58.7	53.5	52.0	46.8	44.8
Difference	4.0	4.3	4.1	4.7	5.3	8.9	6.8	7.1	11.9	14.8	17.6	19.3
3 m from driving lane	66.9	65.4	63.5	63.9	64.6	68.3	74.9	73.6	69.9	69.5	68.2	68.4
4 m from noise barrier No. 2	62.7	61.4	59.0	58.1	59.4	61.8	66.0	65.2	60.2	58.9	55.8	53.0
Difference	4.2	4.0	4.5	5.8	5.2	6.5	8.9	8.4	9.7	10.7	12.4	15.4

3. Simulation of acoustic situation and noise attenuation possibilities at low frequencies

According to free field measurements it is obvious that traffic generated LFN levels up to 31.5 Hz are under indoor SPL limit values in all countries [3], therefore 31.5-200Hz frequency range is analysed in the manuscript. To make simulations 31.5, 63, 125 and 200 Hz discrete frequencies were chosen.

To assign sound power levels for linear sound source, data of measured (in free field conditions) equivalent sound pressure levels 3 m from driving lane (6 m from nearest driving lane axis) was taken and calculated according to Eqs. (1) and (2) (Table 2).

Table 2
Assigned linear sound source sound power levels

1/3 octave band centre frequencies, Hz	L_{eq} at 6 m from nearest driving lane axis, dB	Assigned L_w, W/m (for ½ cylinder domain)
31.5	62.7	0.00002164
63	72.5	0.0002053
125	64.3	0.00003148
200	62.9	0.00002242

To simulate an existing acoustic situation and possibilities to increase the efficiency of noise barriers, COMSOL software (Acoustics model) was chosen and finite element method (FEM) was used. In order to solve the problem a 3D model was created in Acoustic-Solid Interaction Frequency Domain.

Traffic noise was treated as a noise from linear source. Calculation space was created as 1/2 of a cylinder with linear noise source at the centre of a cylinder. Resumptive noise barrier was designed at 4.5 m from the noise source as an infinite length (no lateral sound wave diffraction) and parallel to the linear noise source. The calculation space has 18 m in radius, therefore atmosphere can be treated as homogeneous and influence of meteorological factors, such as wind speed and direction or sound wave refraction from upper air layers, was ignored. Essentially the model deals with: divergence loss (the loss due to geometric spreading), diffraction from obstacles, absorption and reflection from surfaces of cylindrical sound waves.

The sound power level is calculated according well known equations [25]. Basic equations of FEM model are presented below [26].

Solving equations. The Linear noise source sound power levels for cylindrical domain:

$$L_W = L_p + 10\,log_{10}\left(R\right) + 6 - 10\,log_{10}\left(\frac{\rho c}{400}\right). \quad (1)$$

The linear noise source sound power levels for ½ cylindrical domain:

$$P = \left(P_0 10^{L_W/10}\right)/2, \quad (2)$$

where L_w is sound power level of linear source in dB per length unit, dB/m; P is sound power level of linear source in W per length unit, W/m; R is a distance to linear source, m.

The Helmholtz equation:

$$\nabla\left(-\frac{1}{\rho_0}\left(\nabla p - \boldsymbol{q}\right)\right) - \frac{\omega^2}{\rho_0 c^2}\,p = Q. \quad (3)$$

Equation assuming power edge source:

$$\nabla - \frac{1}{\rho_c}\left(\nabla p_t - \boldsymbol{q}\right) - \frac{k_{eq}^2}{\rho_c}\,p_t = 2\sqrt{\frac{P\omega}{\rho_c}}. \quad (4)$$

Boundary conditions. Boundary of ½ of cylinder is assigned as cylindrical wave radiation in a model. Equation assuming cylindrical wave radiation is:

$$-\boldsymbol{n}\left(-\frac{1}{\rho_c}\left(\nabla p_t - \boldsymbol{q}\right)\right) + \left(ik_{eq} + \frac{1}{2r} - \frac{1}{8r\left(1 + ik_{eq}r\right)}\right)\frac{p}{\rho_c} + \frac{r\Delta_T p}{2\left(1 + ik_{eq}r\right)\rho_c} = Q_i. \quad (5)$$

For definition of road surface Sound Hard Boundary conditions were selected:

$$-\boldsymbol{n}\left(-\frac{1}{\rho_c}\left(\nabla p_t - \boldsymbol{q}\right)\right) = 0. \quad (6)$$

Grass covered ground surface has impedance of 3 kPa·s·m−1 (according [15], [27]) boundary conditions:

$$-\boldsymbol{n}\left(-\frac{1}{\rho_c}\left(\nabla p_t - \boldsymbol{q}\right)\right) = -p_t\frac{i\omega}{Z_i}, \quad (7)$$

where ρ is density, kg/m^3 (ρ_0 is reference density, ρ_c is complex-valued density (in models with damping)); q is dipole source, N/m^3; Q is monopole source, 1/s^2; c is speed of sound, m/s; p is pressure, Pa; p_t is total acoustic pressure (sum of the pressure solved for p and the background pressure)), ω is angular frequency, rad/s; f is frequency, Hz; k_{eq} is wave number, m^{-1}; r is the shortest distance from the point $r = (x, y, z)$ on the boundary to the source, m; Z_i is acoustic impedance, Pa·s/m; n is normal vector, which is the natural direction for waveguides.

Noise barrier description. The results of 2 noise barriers efficiency (noise reduction) measurements at low frequencies were similar; therefore, in conformity to measurements results, one model with 3 m height noise barrier was created. FEM calculations are time-consuming and require big computer recourses, therefore simplified model prepared. First of all sound energy reduction was tried to simulate using only macroscopic empirical porous model (which "mimics the bulk losses in certain porous/fibrous materials" [26]) and to imitate barrier play, changing flow resistivity, however simulation results were not corresponding all tested frequencies.

In consideration, that existing barriers have absorbing part as well as structure elements, the simplified model was designed to simulate acoustic field transformation influenced by absorbing material and sound – solid interaction. The noise barrier model was designed from 10 cm width macroscopic porous material part and 2 cm width solid part.

Porous material (domain) is modelled as an equivalent fluid, using empirical Delany-Bazley-Miki model [28, 29] with properties: flow resistivity – 20 kPa·s/m^2, speed of sound and density ρ values are taken from material (air properties)).

The macroscopic empirical porous model can be described by following complex propagation constants:

$$k_c = \frac{\omega}{c}\left[1 + C_1\left(\frac{\rho_0 f}{R_f}\right)^{-C_2} - iC_3\left(\frac{\rho_0 f}{R_f}\right)^{-C_4}\right], \quad (8)$$

$$Z_c = \rho_0 c\left[1 + C_5\left(\frac{\rho_0 f}{R_f}\right)^{-C_6} - iC_7\left(\frac{\rho_0 f}{R_f}\right)^{-C_8}\right], \quad (9)$$

where k_c is wave number; Z_c is characteristic impedance; R_f is flow resistivity, Pa·s/m^2; C_1-C_8 is Miki coefficients to porous material [30].

The solid part of the noise barrier wood, with basic acoustic properties: 1150 kg/m^3 density and 3500 m/s speed of sound. Within Comsol Acoustic-structure Interaction interface, fluid's pressure loads solid domain, and the structural acceleration affects the fluid domain as a normal acceleration across the fluid-solid boundary [26].

Boundary condition for acoustic-structure interaction can be described by equations:

$$\begin{cases} \boldsymbol{F}_p = -\boldsymbol{n}\, p, \\ a_n = \boldsymbol{n}\,\boldsymbol{u}_{tt}, \end{cases} . \quad (10)$$

where F_p is pressure load on the boundaries where the fluid interacts with the solid, Pa; n is the outward-pointing unit normal vector seen from inside the solid domain; a_n is structural acceleration acting on the boundaries between the solid and the fluid.

Structure acoustics is described by equations:

$$\varepsilon_{mn} = \frac{1}{2}\left(\frac{\partial u_m}{\partial x_n} + \frac{\partial u_n}{\partial x_m}\right), \quad (11)$$

$$s = s_0 + C : (\varepsilon - \varepsilon_0 - \alpha\theta),$$

where u is displacement, m; ε is strain (ε_0 is initial strain); s is stress (s_0 is initial stress), N/m^2; C is 4th order elasticity tensor; α is thermal expansion tensor; θ is temperature, K; ":" stands for the double-dot tensor product (or double contraction).

Octagon top was modelled describing only as porous material; meanwhile T-shape barrier had the same properties like noise barrier (with absorbing upper side and 2 cm width wooden part).

Mesh. Considering analysed frequencies and construction modelled noise barriers, model mesh was calibrated for general physics, defining maximum element size 0.25 m, minimum element size 0.002 m, with maximum element growth rate 1.3. Parameters of mesh weren't changed for different frequencies. Examples of model mesh with octagon and T-shape tops showed in Fig. 3.

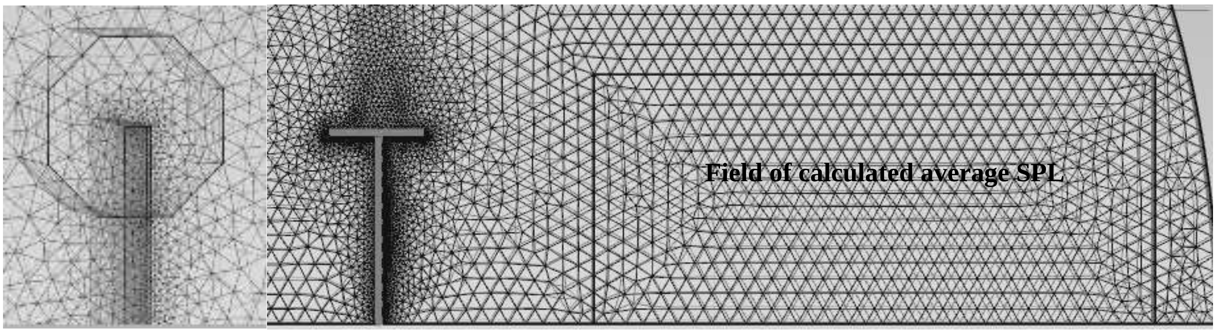

Fig. 3 Examples of model mesh with octagon and T-shape tops

Results of acoustic simulation. Considering the measurements results resumptive models for road traffic noise propagation in free field conditions and with 3 m height noise barrier were created. To compare measurements and simulation with BEM model results, differences between noise levels 3 m from road lane and 4 m behind noise barriers (at 1.5 m height) are presented in Table 3.

Table 3

Differences between noise levels 3 m from road lane and 4 m behind noise barriers. Measurements and simulation results

1/3 octave band centre frequencies, Hz	16	20	25	31.5	40	50	63	80	100	125	160	200
Noise barrier No. 1. Difference between L_{eq} 3m from driving lane and L_{eq} 4 m behind barrier. dB	4.0	4.3	4.1	4.7	5.3	8.9	6.8	7.1	11.9	14.8	17.6	19.3
Noise barrier No. 2. Difference between L_{eq} 3m from driving lane and L_{eq} 4 m behind barrier	4.2	4.0	4.5	5.8	5.2	6.5	8.9	8.4	9.7	10.7	12.4	15.4
Resumptive BEM model Difference between SPL 3m from driving lane and SPL 4 m behind barrier, dB	3.8	4.2	4.9	5.4	6.7	8.7	8.9	9.2	11.4	13.7	14.7	15.5

The best way to improve efficiency of absorptive noise barrier would be to enlarge dimensions (efficient height) of barriers, however in reality it would be difficult and sometimes impossible task, since existing noise barriers are already built and foundation as well as structure elements are selected considering calculations of loads (including wind loads) on it.

One of most popular and effective noise barrier enhancement solutions is to reduce diffraction of sound wave at the top of noise barrier by setting absorptive octagonal or T-shape [31-34]. To simulate acoustic field transformation 0.8 m inner diameter octagonal and 1.5 x 0.1 m T-shape tops, with properties identical to noise barrier properties (4.3 section), were chosen.

Simulated acoustic field transformations showed in Figs. 4-7. The simulation results of average SPL 8 m from noise source (in 4x9 m rectangle) in Table 4.

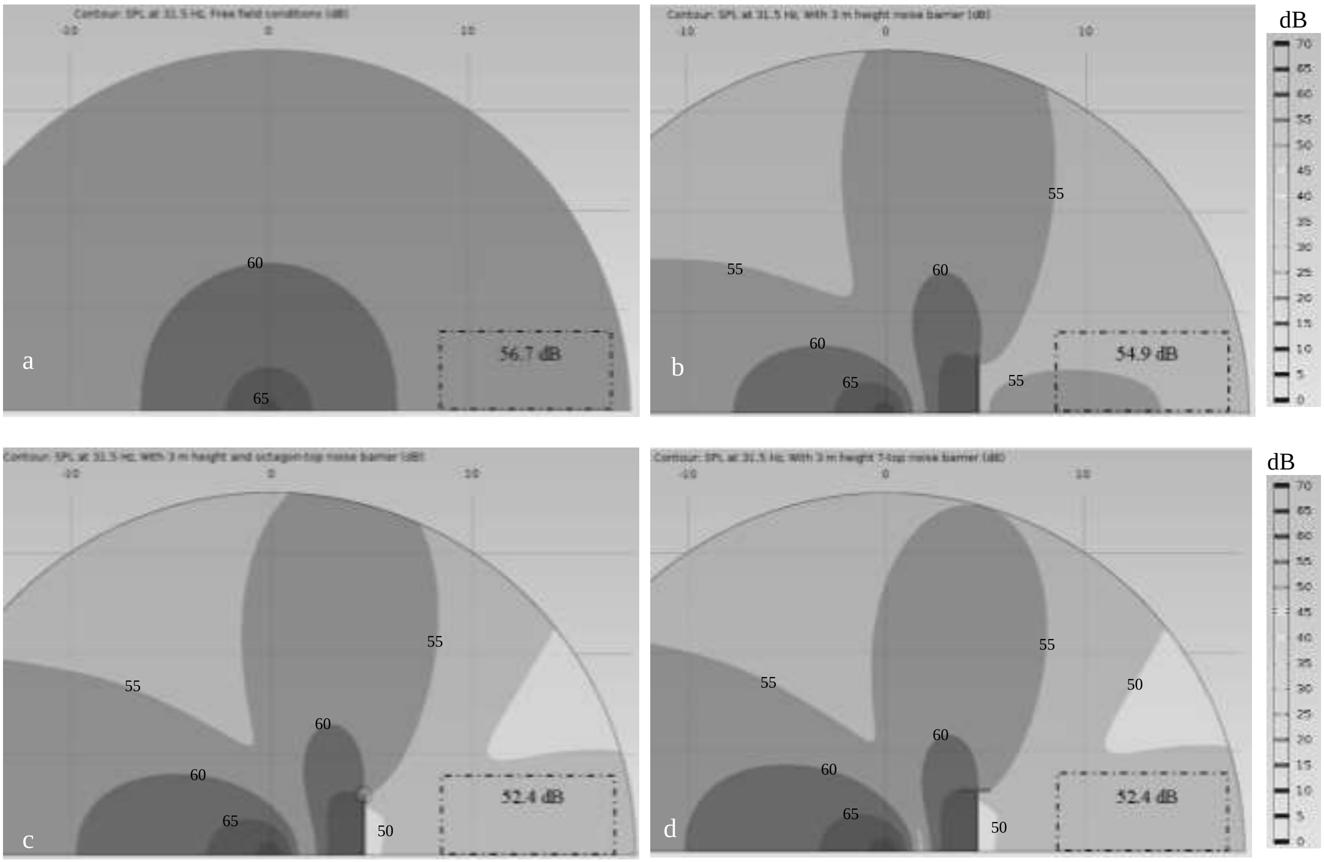

Fig. 4 Simulated acoustic field transformations at 31.5 Hz in a) free field conditions, b) with 3 m height noise barrier, c) with 3 m height noise barrier and octagon top d) with 3 m height noise barrier and T-shape top

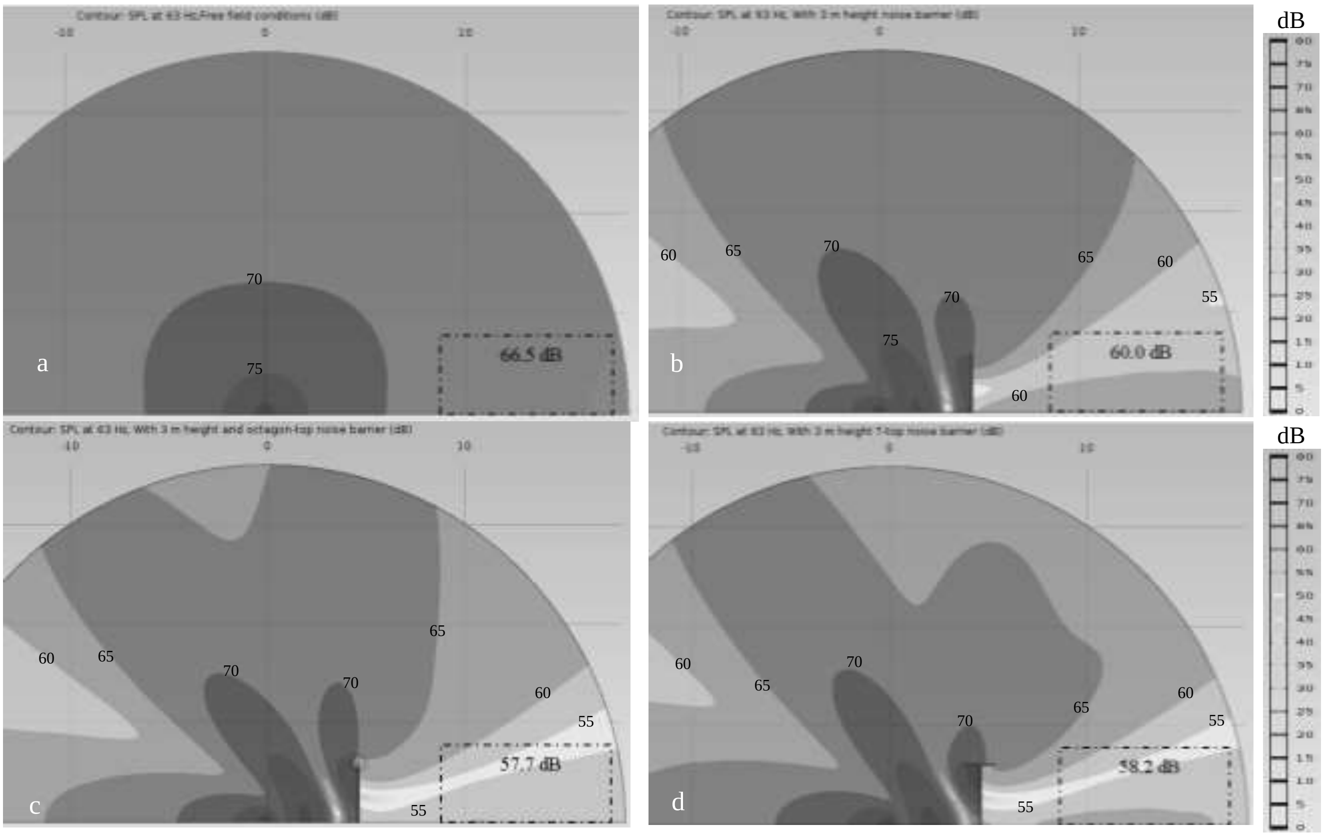

Fig. 5 Simulated acoustic field transformations at 63 Hz in a) free field conditions, b) with 3 m height noise barrier, c) with 3 m height noise barrier and octagon top d) with 3 m height noise barrier and T-shape top

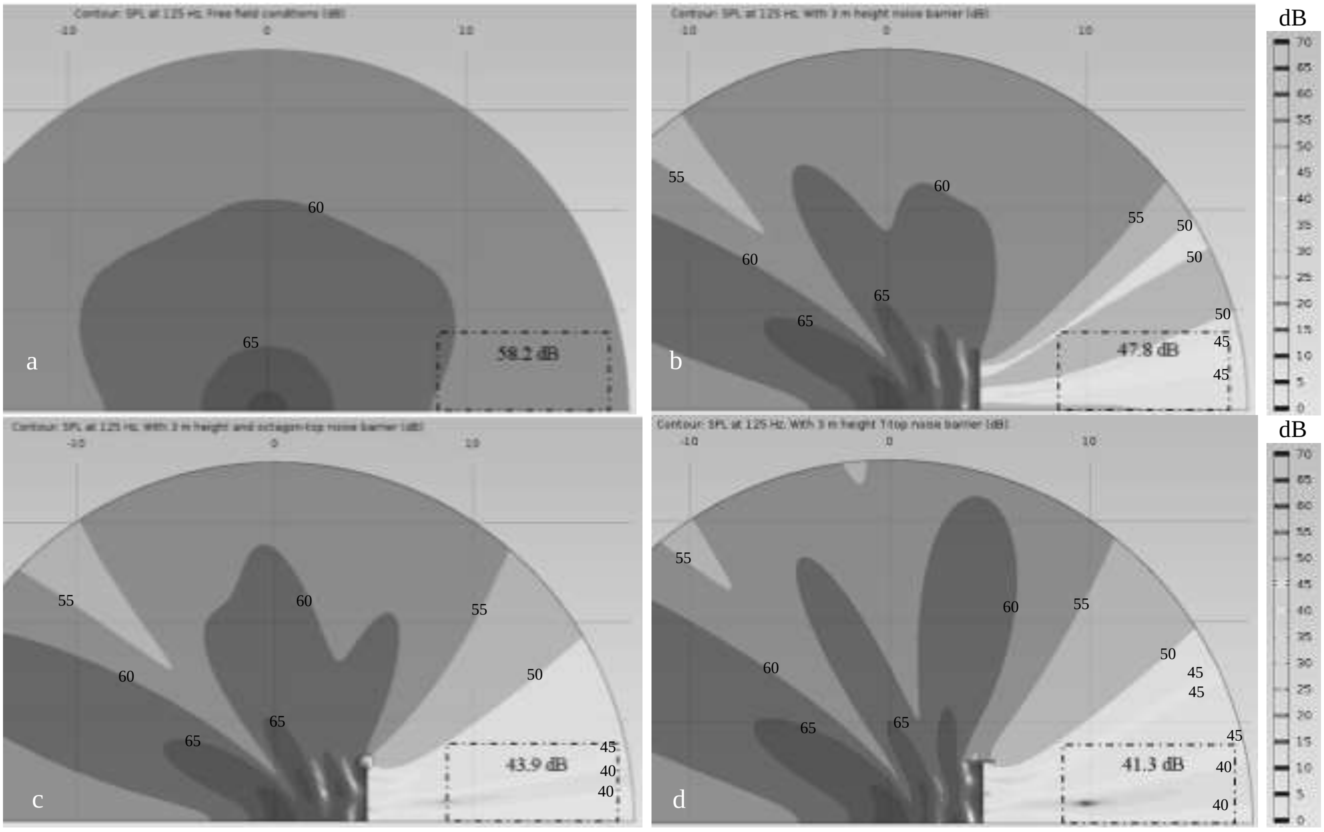

Fig. 6 Simulated acoustic field transformations at 125 Hz in a) free field conditions, b) with 3 m height noise barrier, c) with 3 m height noise barrier and octagon top d) with 3 m height noise barrier and T-shape top

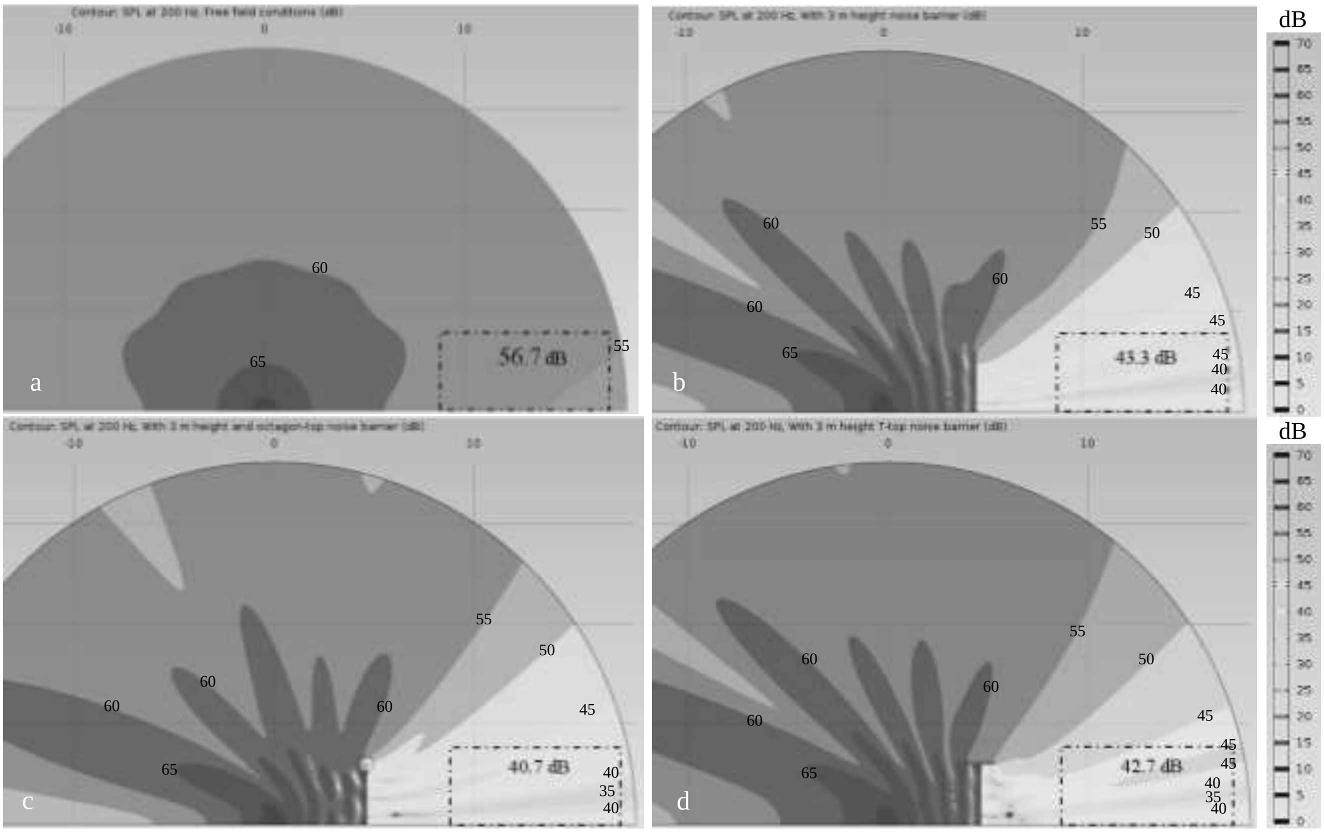

Fig. 7 Simulated acoustic field transformations at 200 Hz in a) free field conditions, b) with 3 m height noise barrier, c) with 3 m height noise barrier and octagon top d) with 3 m height noise barrier and T-shape top

Table 4

Simulation results of average (in 4x9 m rectangle) SPL 8 m from noise source, dB

1/3 octave band centre frequencies, Hz	Free field conditions	With 3 m height noise barrier	With 3 m height and octagon top noise barrier	With 3 m height T-top noise barrier
31.5 Hz	56.7	54.9	52.4	52.4
63 Hz	66.5	60.0	57.7	58.2
125 Hz	58.2	47.8	43.9	41.3*
200 Hz	56.7	43.3	40.7	42.7

*Standing wave node has significant influence on average SPL in rectangle

In [35] is stated, that "barriers are most effective when they are at least three times larger than the wavelength of the major noise contributor". In our case, dimensions of simulated tops are smaller than investigated wavelengths, in spite that, according to results placed in figures and tables of section 4, additional tops make influence on sound wave diffraction. Obvious additional SPL reduction appears next behind noise barrier; father the influence reduces, but still if we take, for example, average SPL in 4x9 rectangle, 4 m behind noise barrier, additional (comparing with simple vertical noise barrier) simulated reduction of SPL is:

- 2.5 dB with octagon and T-Shape tops at 31.5 Hz frequency;
- 2.3 dB with octagon and 1.8 dB with T-Shape tops at 63 Hz frequency;
- 3.9 dB with octagon and 6.5 dB with T-Shape tops at 125 Hz frequency;
- 2.6 dB with octagon and 0.6 dB with T-Shape tops at 200 Hz frequency.

4. Conclusions

Measurements results showed that noise spectrum of investigated heavy traffic busy road has 2 peaks: at 63 Hz and 800-1600 Hz frequencies. Measurements results also showed, that effectiveness of existing noise barriers are better in mid and high frequencies and less at low frequencies - difference between $L_{eq(16\text{-}200Hz)}$ at distance of 3 m from driving lane (in a row with barrier) and 4 m behind noise barrier No. 1 was 13.7 dB and behind barrier No. 2 was 11.7 dB, meanwhile the difference of overall criteria $L_{Aeq(3.6Hz\text{-}20kHz)}$ was respectively 20.6 dB(A) and 18.6 dB(A).

In conformity to measurements results, using FEM with COMSOL software, simplified numerical model was created to simulate acoustical field transformation (at low frequencies) influenced of existing barriers. Also simulation of enhancement by adding octagon and T-shape tops proceeded. The simulation showed, that additional tops can give some additional improvement of noise barriers efficiency even at very low frequencies (for example 2.5 dB improvement at 31.5 Hz frequency).

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INVESTIGATION OF NOISE BARRIERS ENHANCEMENT EFFICIENCY FOR ATTENUATION OF LOW FREQUENCY TRAFFIC NOISE

S u m m a r y

This paper presents investigation of traffic noise barriers enhancement potentiality at low frequencies: regarding measurements results near motorway with 43.3-49.8 percentage of heavy duty, the investigation assesses efficiency of existing (modelled and built according predicted overall A-weighted rated sound levels) noise barriers and simulates (using finite element method) improving of them by adding most common T-shape and octagon-shape tops at low frequencies. According simulation results (model deals with divergence loss, diffraction from obstacles, absorption and reflection from surfaces of cylindrical sound waves), noise barrier enhancement with those tops has influence on additionally 0.6-6.5 dB reduction of SPL at low frequencies in a noise shadow zone.

Keywords: low frequency traffic noise, noise barriers tops.

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