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Noise and Vibration Laboratory



"POLYTECHNICA" UNIVERSITY OF TIMISORA
FACULTY OF MECHANICAL ENGINEERING
Department of Mechanics and Vibration
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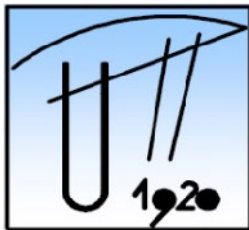
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NONLINEAR VIBRATION ANALYSIS IN THE PRESENCE OF HERTZIAN IMPACT BY MEANS OF THE OPTIMAL AUXILIARY FUNCTIONS METHOD

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Abstract. *The dynamic behaviour of mechanical systems in which surfaces interact according to Hertzian elastic contact theory and the contact force is proportional to indentation exhibits nonlinearity induced by dynamic characteristics, as emphasised in this study. The phenomenon of viscoelastic Hertzian impact is examined by accounting for the continuous nonlinearity of local deformation in the presence of Hertzian contact. The present model consists of two components: the compression and restitution phases. Using the principle of conservation of energy during the two phases, a transcendental equation is derived for the calculation of the hysteresis damping coefficient. The nonlinear differential equations corresponding to the two phases are solved by means of the Optimal Auxiliary Functions Method (OAFM) and the obtained results are compared with numerical results for validation purposes.*

Key words: *Hysteresis damping coefficient, OAFM, Impact model, Hertzian contact*

1. INTRODUCTION

The Hertzian impact theory, first introduced by Heinrich Hertz in 1882 [1], provides a foundational framework for understanding the mechanics of contact between smooth, elastic, and non-adhesive bodies and is particularly valuable in material science, where understanding the mechanical properties under contact loads is essential. For instance, in the analysis of rolling bearings, calculations of Hertzian contact characteristics facilitate predictions regarding bearing components' behaviour. Similarly, in gear design, applying Hertzian analysis aids in optimising gear tooth profiles, which minimises pitting and wear, thereby enhancing durability and performance.

The integration of Hertzian contact theory with vibration analysis reveals several nonlinear effects that complicate the dynamic response of mechanical systems. For instance, Hess et al. [2] demonstrated that when dynamic excitation is applied, there is a reduction in the mean normal contact compression relative to static deflection. This reduction leads to a smaller contact area and subsequently a decrease in the average friction force. Additionally, Rigaud and Perret-Liaudet [3] explored both harmonic and subharmonic excitations in preloaded

Hertzian contact. Their studies indicate that as the input increases, the system exhibits a softening behaviour due to the non-linear stiffness intrinsic to Hertzian contacts. In another study, the same authors investigated the response to order-2 subharmonic excitation, employing the method of multiple scales to elucidate the onset of contact loss and its role in initiating wide-range resonance phenomena [4].

The theoretical insights gained from the integration of Hertzian contact mechanics with vibration analysis have significant practical implications. These findings are particularly relevant in the design and optimisation of mechanical components such as bearings, gears, and other machinery where dynamic loads and contact interactions are critical. Accurate modelling of these interactions mitigates the risk of premature failure and enhances system performance by enabling more precise predictions of behaviour under dynamic conditions. Many researchers developed such theoretical insights based on different adequate techniques. Ma et al. [5] employed the Harmonic Balance Method in conjunction with discrete Fourier transforms to predict contact loss at a sphere-plane contact interface. The Multiple Scale Method and the shooting method combined with a continuation technique are applied by Liaudet and Rigaud [6] in analysing the impact oscillator governed by Hertz stiffness. The Harmonic Balance Method, the Multiple Scale Method and an exact method are used by Xiao et al. [7] to examine the natural frequency of undamped free vibration of a mass interacting with Hertzian contact stiffness.

In this paper, a reliable and efficient analytical technique, namely the Optimal Auxiliary Functions Method (OAFM) [8-11], will be used to investigate Hertzian impact problems.

Obviously, complementing theoretical and numerical approaches, experimental investigations have advanced the empirical understanding of Hertzian impact phenomena. Many researchers have conducted experimental investigations, as reported in [12-15].

Impact is a complex physical phenomenon characterised by a very short duration and high levels of rapid energy dissipation, causing a sudden change in the

direction of impact. In general, the impact phenomenon between two materials is divided into two phases: the compression phase and the restitution phase.

In this paper, we consider an elastic sphere-plane contact with the impact force modelled as:

$$F(t) = \begin{cases} Kz^{3/2} + \mu z^{3/2} \dot{z}, & 0 < z \leq z_{\max}, \dot{z} \geq 0 \\ \Delta \left(K\bar{z}^{3/2} + \mu \bar{z}^{3/2} \dot{\bar{z}} \right), & z_e \leq z \leq z_{\max}, \dot{z} \leq 0 \end{cases} \quad (1)$$

where the first expression stands for the compression phase, while the second one stands for the restitution phase. Here, z is the elastic deformation, $\bar{z} = z - z_e$, in which z_e is the so-called remaining surface deformation, and Δ will be defined later.

2. EVALUATION OF THE REMAINING SURFACE DEFORMATION

If the masses of the two materials in contact are m_1 and m_2 , then the equivalent mass is

$$m = \frac{m_1 m_2}{m_1 + m_2}, \quad (2)$$

and, according to Newton's law, the dynamic equations of the system are given by:

$$\begin{aligned} m\ddot{z} + Kz^{3/2} + \mu z^{3/2} \dot{z} &= 0 \quad (\text{compression}) \\ m\ddot{z} + K(z - z_e)^{3/2} + \mu(z - z_e)^{3/2} \dot{z} &= 0 \quad (\text{rest.}) \end{aligned} \quad (3)$$

If the velocity of deformation is $v = \dot{z}$, the first expression in Eq. (3) gives:

$$\frac{m\dot{v}}{K + \mu v} = -z^{3/2} \quad (4)$$

From the last equation, after simple manipulations including multiplication by dz , one obtains the following equation with separable variables:

$$\frac{m\dot{v}dv}{K + \mu v} = -z^n dz, \quad n = \frac{3}{2} \quad (5)$$

A first integral of Eq. (5) is:

$$\frac{m}{\mu} \left[v - \frac{K}{\mu} \ln(\mu v + K) \right] + \frac{z^{n+1}}{n+1} = c_1 \quad (6)$$

The initial conditions are imposed:

$$t = 0 : v = v_0, z = 0 \quad (7)$$

such that a particular solution of Eq. (4) is:

$$\frac{z^{n+1}}{n+1} = \frac{m}{\mu} (v_0 - v) + \frac{mv}{\mu} \ln \left(\frac{K + \mu v}{K + \mu v_0} \right) \quad (8)$$

At the end of the compression phase, the deformation velocity is $v = 0$, and the deformation depth reaches an extremum. More precisely, $z = z_{\max}$ provided that $d^2z / dt^2 < 0$.

Indeed,

$$\ddot{z} = -\frac{1}{2} (Kz^n + z^n \dot{z}) < 0 \quad (9)$$

and the maximum value of the deformation becomes:

$$z_{\max} = \left[\frac{(n+1)m}{\mu} v_0 - \frac{mK(n+1)}{\mu^2} \ln \left(1 + \frac{\mu v_0}{K} \right) \right]^{\frac{1}{n+1}} \quad (10)$$

The relation between relative acceleration and velocity can be obtained from the first expression in Eq. (3):

$$\ddot{z}(v) = -(K + \mu v) \left[\frac{m}{\mu} (v_0 - v) + \frac{mK}{\mu^2} \ln \left(\frac{K + \mu v}{K + \mu v_0} \right) \right] \quad (11)$$

At the moment of separation t^+ , we have that:

$$\dot{z}(t^+) = -c_r v_0, \quad z(t^+) = z_e \quad (12)$$

where c_r is the restitution coefficient.

As is known,

$$v = \frac{dz(t)}{dt} = \frac{d}{dt} (z(t) - z_e) \quad (13)$$

so the second expression in Eq. (3) can be rewritten as:

$$m \frac{d\dot{z}}{dz} \dot{z} + \Delta (K + \mu \dot{z}) (z(t) - z_e)^n = 0 \quad (14)$$

or in the equivalent form:

$$\frac{m}{\Delta \mu} \left(1 - \frac{K}{\mu} \frac{\mu}{\mu v + K} \right) dv = -(z(t) - z_e)^n \quad (15)$$

By integrating Eq. (15), one obtains:

$$c_2 = -\frac{m}{\Delta \mu} \left[-c_r v_0 - \frac{K}{\mu} \ln \Delta (K - \mu c_r v_0) \right] - \frac{(z - z_e)^{n+1}}{n+1} \quad (16)$$

or

$$\frac{(z - z_e)^{n+1}}{n+1} = -\frac{m}{\mu} (v - c_r v_0) + \frac{mK}{\Delta \mu^2} \ln \frac{K + \mu v}{K - \mu c_r v_0} \quad (17)$$

The maximum value of the deformation is obtained for $v = 0$, and therefore

$$z_{\max} - z_e = (-1)^{\frac{1}{n+1}} \left[\frac{(n+1)m c_r v_0}{\Delta \mu} + \frac{(n+1)K}{\Delta \mu^2} \ln \left(1 - \frac{m c_r v_0}{K} \right) \right]^{\frac{1}{n+1}} \quad (18)$$

The remaining surface deformation z_e can be obtained from Eqs. (10) and (18):

$$\begin{aligned} z_e &= \left[\frac{(n+1)m v_0}{\mu} - \frac{mK(n+1)}{\mu^2} \ln \left(1 + \frac{\mu v_0}{K} \right) \right]^{\frac{1}{n+1}} - \\ &(-1)^{\frac{1}{n+1}} \left[\frac{(n+1)m c_r v_0}{\Delta \mu} + \frac{(n+1)K}{\Delta \mu^2} \ln \left(1 - \frac{\mu c_r v_0}{K} \right) \right]^{\frac{1}{n+1}} \end{aligned} \quad (19)$$

According to Hertzian impact theory, $n = 3/2$, and the remaining surface deformation can be rewritten as:

$$z_e = \left[\frac{3mv_0}{2\mu} - \frac{3mK}{2\mu^2} \ln \left(1 + \frac{\mu v_0}{K} \right) \right]^{\frac{2}{3}} - \left[\frac{3mc_r v_0}{2\Delta\mu} + \frac{3mK}{2\Delta\mu^2} \ln \left(1 - \frac{\mu c_r v_0}{K} \right) \right]^{\frac{2}{3}} \quad (20)$$

This value is unknown at this stage. The remaining surface deformation can be determined if the hysteresis damping coefficient is known. In the next section, the transcendental equation will be presented from which the hysteresis damping coefficient can be found.

3. DETERMINATION OF THE HYSTERESIS DAMPING COEFFICIENT

The hysteresis damping coefficient will be determined in the context of a sphere-plane impact depicted in Fig. 1.

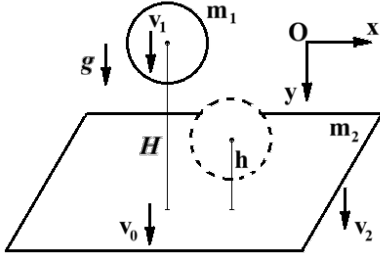


Fig. 1 Schematic of an impact between a sphere and a plane

The velocities of the sphere and of the plane will be denoted by the indices 1 and 2, respectively, while the (-) and (+) signs will be used to identify their values before and after the impact, respectively. Thus, four velocity values are considered: $v_1^{(-)}$ and $v_2^{(-)}$ before the impact, and $v_1^{(+)}$ and $v_2^{(+)}$ after the impact when the deformation attains the maximum value z_{max} .

Before the impact, a relative velocity may be identified as:

$$\dot{z}^{(-)} = v_0 = v_1^{(-)} - v_2^{(-)} \quad (21)$$

while the velocity during the separation phase is:

$$\dot{z}^{(+)} = v_1^{(+)} - v_2^{(+)} \quad (22)$$

and the coefficient of restitution c_r will be:

$$c_r = -\frac{\dot{z}^{(+)}}{v_0} \quad (23)$$

The kinetic energy lost during the impact is:

$$\Delta E = \frac{1}{2} m_1 v_1^{(-)2} + \frac{1}{2} m_2 v_2^{(-)2} - \left[\frac{1}{2} m_1 v_1^{(+2)} + \frac{1}{2} m_2 v_2^{(+2)} \right] \quad (24)$$

Applying conservation of momentum to the impact gives:

$$m_1 v_1^{(-)} + m_2 v_2^{(-)} = m_1 v_1^{(+)} + m_2 v_2^{(+)} \quad (25)$$

and from the above description, one can conclude that:

$$\Delta E = \frac{1}{2} \frac{m_1 m_2}{m_1 + m_2} v_0^2 (1 - c_r^2) = \frac{1}{2} m v_0^2 (1 - c_r^2) \quad (26)$$

The remaining surface deformation implies energy dissipation during the compression and restitution phases, given by:

$$\begin{aligned} \Delta E_1 &= \int_0^{z_{max}} K z(t)^n dz(t) + \int_{z_{max}}^{z_e} \Delta K (z(t) - z_e)^n dz(t) = \\ &= \frac{K}{n+1} z_{max}^{n+1} - \frac{\Delta K}{n+1} (z_{max} - z_e)^{n+1} \end{aligned} \quad (27)$$

which, after simple computations, leads to:

$$\begin{aligned} \Delta E_1 &= \frac{K m v_0}{\mu} - \frac{m K^2}{\mu^2} \ln \left(1 + \frac{\mu v_0}{K} \right) + \\ &\frac{K m c_r v_0}{\mu} + \frac{K^2 m}{\mu^2} \ln \left(1 - \frac{\mu c_r v_0}{K} \right) \end{aligned} \quad (28)$$

Considering the damping force during the compression and restitution phases, the associated work will be:

$$\begin{aligned} \Delta E_2 &= \int_{0(z=v_0)}^{z_{max}(z=0)} \mu z(t)^n \dot{z}(t) dz(t) + \int_{z_{max}(z=0)}^{z_e(z=-c_r v_0)} \Delta \mu (z(t) - z_e)^n \\ &\dot{z}(t) dz(t) = -\mu \int_{v_0}^0 \frac{z^{n+1}}{n+1} dz - \Delta \mu \int_0^{-c_r v_0} \frac{(z(t) - z_e)^{n+1}}{n+1} dz(t) \end{aligned} \quad (29)$$

which, using the above results, leads to:

$$\begin{aligned} \Delta E_2 &= \int_0^{v_0} \left[m(v_0 - v) + \frac{K m}{\mu^2} \ln \left(1 + \frac{\mu v}{K} \right) - \frac{K m}{\mu} \ln \left(1 + \frac{\mu v_0}{K} \right) \right] dv + \\ &\int_0^{-c_r v_0} \left[m v + m c_r v_0 + \frac{K m}{\mu} \ln \left(1 - \frac{\mu c_r v_0}{K} \right) - \frac{K m}{\mu} \ln \left(1 + \frac{\mu}{K} \right) \right] dv = \\ &-\frac{1}{2} m v_0^2 (1 - c_r^2) - \frac{m K v_0}{\mu} (1 + c_r) + \frac{m K^2}{\mu^2} \ln \left(1 + \frac{\mu v_0}{K} \right) - \\ &\frac{m K^2}{\mu^2} \ln \left(1 + \frac{\mu}{K} \right) \end{aligned} \quad (30)$$

According to the principle of energy conservation, the lost kinetic energy is the sum of the energy dissipated by the remaining surface deformation and that dissipated by damping, so that:

$$\Delta E = \Delta E_1 + \Delta E_2 \quad (31)$$

which, after substituting its components, leads to:

$$\frac{\mu v_0}{K} (1 + c_r) + \ln \left(1 - \frac{\mu c_r v_0}{K} \right) - \ln \left(1 + \frac{\mu v_0}{K} \right) = 0 \quad (32)$$

Finally, following the above developments, the hysteresis damping coefficient will be found from the transcendental equation:

$$\frac{\mu v_0}{K} + \ln \frac{K - \mu c_r v_0}{1 + \mu v_0} = 0 \quad (33)$$

whose solution requires a numerical procedure.

4. NUMERICAL VERIFICATIONS

For the model presented in Fig. 1, the equation of motion for the compression phase will be:

$$m_b \ddot{y} + K(y - H)^{\frac{3}{2}} + \mu(y - H)^{\frac{3}{2}} \dot{y} = m_b g, \quad (34)$$

with the initial conditions

$$y(0) = H, \dot{y}(0) = v_0^* \quad (35)$$

To solve the dynamical system defined above efficiently, we will use the following transformation:

$$y - H = z + z_{st} \quad (36)$$

in which z_{st} represents the static impact compression defined by:

$$z_{st} = \left(\frac{m_b g}{K} \right)^{2/3} \quad (37)$$

After substitution in Eq. (34), one obtains

$$\begin{aligned} \frac{3}{2} w'' + (w+1)^{3/2} + \frac{\mu \Omega}{K} (w+1)^{3/2} w' &= 1, \\ w(0) = 0, w'(0) &= \frac{v_0^*}{z_{st}} = v_0 \end{aligned} \quad (38)$$

in which

$$w(\tau) = \frac{z(t)}{z_{st}}; \tau = \Omega t, \Omega^2 = \frac{3K}{2m_b} z_{st}^{1/2}, w' = \frac{dw}{d\tau} \quad (39)$$

Since $w \ll 1$, the term $(w+1)^{3/2}$ in Eq. (38) may be approximated by expanding it in a Taylor series:

$$(w+1)^{3/2} \approx 1 + \frac{3}{2}w + \frac{3}{8}w^2 - \frac{1}{16}w^3 + \frac{3}{128}w^4 \quad (40)$$

and Eq. (38) may be expressed in dimensionless form:

$$\begin{aligned} w'' + w + \frac{1}{4}w^2 - \frac{1}{24}w^3 + \frac{1}{64}w^4 + \\ \frac{\mu \Omega}{K} \left(\frac{2}{3} + w + \frac{1}{4}w^2 - \frac{1}{24}w^3 + \frac{1}{64}w^4 \right) w' &= 0 \end{aligned} \quad (41)$$

with initial conditions:

$$w(0) = 0, w'(0) = v_0 \quad (42)$$

For the second phase, corresponding to restitution, the governing equation will be:

$$m_b \ddot{y} + \lambda K(y - z_e)^{3/2} + \lambda \mu y - z_e)^{3/2} \dot{y} = m_b g \quad (43)$$

By employing the transformation

$$\begin{aligned} \bar{w}(\tau) &= \frac{y - z_e - \bar{z}_{st}}{\bar{z}_{st}}, \bar{z}_{st} = \left(\frac{m_b g}{\lambda K} \right)^{2/3}, \\ \bar{\tau} &= \bar{\Omega} t, \bar{\Omega}^2 = \frac{3K}{2m_b \lambda} \bar{z}_{st}^{1/2} \end{aligned} \quad (44)$$

the equation may be rewritten by means of the Taylor series expansion as:

$$\begin{aligned} \bar{w}'' + \lambda \left(1 + \bar{w} + \frac{1}{4}\bar{w}^2 - \frac{1}{24}\bar{w}^3 + \frac{3}{128}\bar{w}^4 \right) + \\ \frac{\lambda \mu \bar{\Omega}}{K} \left(\frac{2}{3} + \bar{w} + \frac{1}{4}\bar{w}^2 - \frac{1}{24}\bar{w}^3 + \frac{3}{128}\bar{w}^4 \right) \bar{w}' &= 0 \end{aligned} \quad (45)$$

where $\bar{w}' = \frac{d\bar{w}}{d\bar{\tau}}$.

Let τ^M denote the value of τ at which $w(\tau)$ reaches its maximum. Eq. (41) is defined for $\tau \in [0, \tau^M]$, while Eq. (45) is defined for $\bar{\tau} = \tau - \tau^M \geq 0$.

The value of the coefficient μ is obtained from Eq. (32), and λ is determined from the conditions

$$w(\tau^M) = \bar{w}(0) \text{ or } w'(\tau^M) = \bar{w}'(0) = 0 \quad (46)$$

For the nonlinear differential equation (45), the initial conditions are

$$\bar{w}(0) = w(\tau^M), w'(0) = 0 \quad (47)$$

Further, an efficient analytical procedure, namely the Optimal Auxiliary Functions Method (OAFM) [8-11], will be employed to find the solutions for the compression phase governed by Eqs. (41) and (42) and for the restitution phase governed by Eqs. (45) and (47).

The OAFM solution procedure is applicable to any differential equation that can be written in the general form

$$L[W(\tau)] + N[W(\tau)] + \varphi(\tau) = 0, \tau \in D \quad (48)$$

with the initial conditions given by the boundary operator

$$B \left[W(\tau), \frac{dW(\tau)}{d\tau} \right] = 0 \quad (49)$$

where L and N represent the linear and nonlinear operators, $W(\tau)$ is an unknown function, D is the domain of interest and φ is a known function to be specified.

The OAFM analytical solution will be sought in the form:

$$\bar{W}(\tau) = W_0(\tau) + W_1(\tau, C_1, C_2, \dots, C_n) \quad (50)$$

where C_i are n convergence-control parameters whose optimal values will ensure rapid convergence of the solution.

The initial approximation $W_0(\tau)$ will be identified as a solution to the simple differential equation

$$L(W_0(\tau)) = \varphi(\tau) \quad (51)$$

with the initial conditions imposed through the boundary operator (49):

$$B\left[W_0(\tau), \frac{dW_0(\tau)}{d\tau}\right] = 0 \quad (52)$$

and the solution may be expressed as:

$$W_0(\tau) = \sum_{k=1}^{n_1} a_k f_k(\tau) \quad (53)$$

using the coefficients a_k and the functions $f_k(\tau)$ which will be identified for each case.

Within the OAFM framework [8-11], the unknown first approximation W_1 will be of the form:

$$W_1(\tau, C_1, C_2, \dots, C_n) = \sum_{j=1}^{n_2} H_j(f_k, g_i, C_l), \quad (54)$$

$$B\left[W_1, \frac{dW_1}{d\tau}\right] = 0, \quad l = \overline{1, n}$$

where H_j are the "auxiliary functions" specific to OAFM, which depend on the unknown parameters C_l , on some functions f_k involved in Eq. (53) and on some functions $g_i(\tau)$ involved in the nonlinear operator.

To finalise the solution procedure, the optimal values of the convergence-control parameters $C_1, \dots, C_n$ must be identified via various mathematical techniques to minimise the residual error given by the obtained approximate analytical solution.

Following the above-described steps, the nonlinear differential equation (41) will be solved using OAFM.

For this purpose, the linear and nonlinear operator may be chosen as

$$L[W(\tau)] = W''(\tau); \quad N[W(\tau)] = W + \frac{1}{4}W^2 - \frac{1}{24}W^3 + \frac{3}{128}W^4 + \frac{\mu\Omega}{K}W' \left(\frac{2}{3} + W + \frac{1}{4}W - \frac{1}{24}W^3 + \frac{3}{128}W^4 \right) \quad (55)$$

First, one can obtain the initial approximation $W_0(\tau)$ from Eqs. (42) and (51):

$$L(W_0(\tau)) = W_0''(\tau) = 0, \quad W_0(0) = 0, \quad W_0'(0) = v_0 \quad (56)$$

so that

$$W_0(\tau) = v_0\tau \quad (57)$$

For this initial approximation, one can compute the nonlinear operator N using Eq. (55) as:

$$N[W_0(\tau)] = v_0\tau - \frac{v_0^3}{24}\tau^3 + \frac{3v_0^4}{128}\tau^4 + \frac{\mu\Omega v_0}{K} \left[\frac{2}{3} + v_0\tau + \frac{v_0^2}{4}\tau^2 - \frac{v_0^3}{24}\tau^3 + \frac{3v_0^4}{128}\tau^4 \right] \quad (58)$$

For the constructed first approximation, the initial conditions are:

$$W_1(0, C_1, C_2, \dots, C_n) = W_1'(\tau, C_1, C_2, \dots, C_n) = 0 \quad (59)$$

According to the OAFM procedure, considering Eqs. (58) and (59), one may express the first approximation as:

$$W_1(\tau, C_1, C_2, C_3) = C_1\tau^2 + C_2\tau^3 + C_3\tau^4 \quad (60)$$

or alternatively

$$W_1^*(\tau, C_1, C_2, C_3, C_4) = C_1\tau^2 + C_2\tau^3 + C_3\tau^4 + C_4\tau^5 \quad (61)$$

The final solutions for Eqs. (41) and (42) are

$$\bar{W}(\tau, C_1, C_2, C_3) = v_0\tau + C_1\tau^2 + C_2\tau^3 + C_3\tau^4 \quad (62)$$

and

$$\bar{W}(\tau, C_1, C_2, C_3, C_4) = v_0\tau + C_1\tau^2 + C_2\tau^3 + C_3\tau^4 + C_4\tau^5 \quad (63)$$

Further, the approximate solutions for the restitution phase, governed by Eqs. (45) and (47), are

$$\begin{aligned} \bar{\bar{W}}(\bar{\tau}) &= W(\tau^M) + \frac{1}{2}\bar{z}_{st}(\tau - \tau^M)^2(1 + \lambda C_4) + \\ &\frac{\lambda\mu}{K} \left[\frac{2}{3}\bar{z}_{st} + U(\tau^M) - \frac{U^3(\tau^M)}{24\bar{z}_{st}^2} + \frac{3U^4(\tau^M)}{128\bar{z}_{st}^3} \right] \frac{(\tau - \tau^M)^3}{6} C_5 + \\ &\lambda \left[\bar{z}_{st} + \frac{1}{4}W(\tau^M) - \frac{W^2(\tau^M)}{16\bar{z}_{st}} + \frac{3W^3(\tau^M)}{64\bar{z}_{st}^2} \right] \frac{(\tau - \tau^M)^4}{12} C_6 \end{aligned} \quad (64)$$

$$\begin{aligned} \bar{\bar{W}}(\bar{\tau}) &= W(\tau^M) + \frac{1}{2}\bar{z}_{st}(\tau - \tau^M)^2(1 + \lambda C_4) + \\ &\lambda \left[\bar{z}_{st} + \frac{1}{4}W(\tau^M) - \frac{W^2(\tau^M)}{16\bar{z}_{st}} + \frac{3W^3(\tau^M)}{64\bar{z}_{st}^2} \right] \frac{(\tau - \tau^M)^5}{48} C_5 \end{aligned} \quad (65)$$

The results obtained by means of the OAFM will be compared with the results obtained by numerical integration using the classical fourth-order Runge-Kutta method (RK4). This validation step can demonstrate the very high accuracy of the proposed procedure.

For the specific numerical values $v_0 = 0.5$, $K = 6.858 \cdot 10^5$, $g = 9.81$, $m_b = 1$, it follows that $\lambda = 1.13$ and $\mu = 9.6925 \cdot 10^4$, $\tau^M = 0.008795527$, $u(\tau^M) = 0.00311214$.

Minimising the residual associated with the obtained solutions gives the following values of the convergence-control parameters for the compression and restitution phases in Eqs. (62) and (64), respectively:

$$\begin{aligned} C_1 &= 7.132625145, \quad C_2 = -2385.000785, \\ C_3 &= -36265.59789, \quad C_4 = -70.82318351, \\ C_5 &= -79.4763953, \quad C_6 = -35060.7111 \end{aligned} \quad (66)$$

A comparison between the approximate solution of Eq. (41) and the numerical solution is presented in Fig. 2.

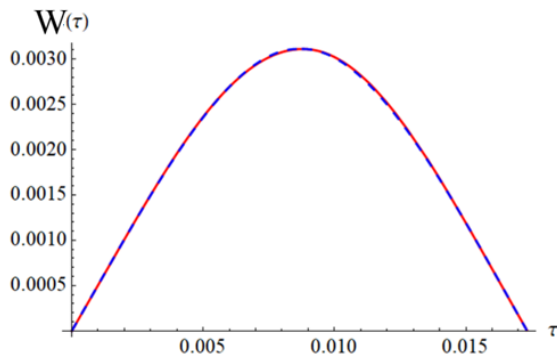


Fig. 2 Comparison between the OAFM and numerical solution : — numerical — — — analytical

The results reveal a very accurate solution obtained by our procedure and demonstrate the great potential of our method. To the best of our knowledge, the analytical solution of the nonlinear dynamical system (41) is not yet known in the scientific literature.

5. CONCLUSIONS

In this work, a model of viscoelastic sphere-plane impact is presented without neglecting the continuous nonlinearity associated with the Hertzian contact. Such dynamic behaviour is characterised by an extremely short duration, substantial impact forces, severe accelerations, and significant energy dissipation.

The model proposed in this study is based on a two-component structure related to elastic energy conservation and viscous dissipation. The analysis covers the compression and restitution phases while accounting for the remaining surface deformation.

An important challenge in modelling this impact behaviour was the derivation of the hysteresis damping coefficient involved in the investigated phenomenon, since the impact between the two colliding materials involves a sophisticated energy transfer process.

Based on the principle of conservation of energy for the compression and restitution phases and taking account of the coefficient of restitution, the transcendental equation for the identification of the hysteresis damping coefficient is derived independently of the remaining surface deformation ratio.

A closed-form expression for the remaining surface deformation is derived based on the identified hysteresis damping coefficient.

This work addresses the challenges of strongly nonlinear systems by analysing the governing differential equations of a rigid sphere in contact with a rigid plane.

An approximate analytical method, namely the Optimal Auxiliary Functions Method (OAFM) was employed to obtain highly accurate solutions for both phases of the Hertzian impact. The core of this procedure lies in incorporating auxiliary functions alongside optimal convergence-control parameters to derive a very accurate solution. The optimal values of the convergence-control parameters are derived via a rigorous mathematical framework and contributed to the accuracy of the investigation.

The main novelties of our work are the construction of an impact force model depending on the parameter Δ ; the evaluation of the hysteresis damping coefficient; the evaluation of the remaining surface deformation in closed form; and the determination of the sphere's displacement in both phases.

Hertzian impact mechanics remains an essential area of study with applications that span key sectors such as material science, mechanical design and geophysics.

Through a combination of theoretical analysis, numerical investigation and experimental verification and validation, the field continues to evolve and offers guidelines for designing high-quality components that remain durable under high-impact stress resulting from contact between smooth, elastic and non-adhesive bodies.

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RESULTS OF MODELING THE PROPAGATION OF SOUND IN THE SOUND CHANNEL IN THE WATERS OF THE BLACK SEA

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Abstract. *Sound propagation models for underwater sound channels were developed based on the models established at the I. Sikorsky National Technical University of Ukraine. This paper presents the physical and mathematical models and their software implementation. The developed software classes were used to generate acoustic ray diagrams using actual sound speed profile data from the Black Sea. The winter and summer ray diagrams differ because of seasonal variations in the sound channel. Numerical calculations were performed, and the results were analysed.*

Key words: *Sound propagation, Sound channel, Sound speed profile, Mathematical model, Acoustic ray diagram*

1. INTRODUCTION

This article presents underwater sound propagation models and simulations performed using software developed by the authors.

The topic under discussion is part of the broader field of underwater communications, an area of great importance today, given the growing role of the oceans in the economy, science, and security. Underwater communications, monitoring and surveillance in the Black Sea are more critical than ever during the current period of war.

Communication channels based on electromagnetic waves are established in all possible media: the atmosphere, outer space, and the world's oceans. Ocean water is conductive, which means that, in principle, electromagnetic waves cannot propagate over long distances. Underwater communication can be achieved using acoustic waves. Under certain conditions, sound and infrasound waves can propagate through water over distances of hundreds or even thousands of kilometers with relatively low attenuation.

Based on the sound channel model created at the I. Sikorsky National Technical University of Ukraine [1], the authors have developed a mathematical model and implemented it in software. Winter and summer sound speed profiles for the Black Sea were generated and used as inputs to numerical simulations. The simulation results are visualised and discussed.

The article is structured as an overview of the physical model of underwater sound propagation, the mathematical model, the software implementation of the model, modeling of the aquatic media using sound speed profiles, sound propagation simulations, the visualisation of numerical simulations, and a discussion of some results.

2. MODELLING UNDERWATER SOUND PROPAGATION

Sound propagation in water is described by the wave equation, which is solved under appropriate boundary and initial conditions. Various modeling approaches, including ray theory, have been developed to simplify the calculations.

Ray tracing is a method for calculating the path of waves or particles through a heterogeneous medium containing regions with varying propagation speeds (variable speed gradient), differing absorption characteristics, and reflective surfaces. In such a setup, wavefronts can bend, change direction, and reflect off surfaces, thereby complicating the analysis. The ray tracing method simplifies the problem by introducing idealised narrow rays and tracking their paths through the medium [2]. Simpler problems can be analysed by examining a few rays using less complex mathematics, whereas a more detailed analysis can be achieved by using software to trace numerous rays [3].

Ray theory does not explain phenomena such as interference and diffraction, which require a wave-based description that accounts for phase.

2.1. Base model

In the model, the aquatic medium is divided into horizontal layers characterised by a known sound speed profile, $c = c(z)$, expressed as a function of depth.

It is assumed that the medium is vertically stratified into layers characterised by an approximately linear variation in the speed of sound, or equivalently, by a constant gradient, g_{ci} . When propagating through such a layer, the sound ray follows a circular arc, with the sound bending (refracting) toward the region of lower sound speed.

2.2. Physical model

Modeling a specific acoustic situation requires consideration of the relevant sound characteristics. Depending on the modeling objectives, sound propagation can be represented using either waves or rays. Relevant characteristics include frequency, wavelength, period, amplitude, sound intensity level (SIL), speed, and direction of propagation.

Sound propagation in an aquatic environment involves phenomena such as refraction, attenuation, ionic relaxation, reflection, absorption, scattering, reverberation, diffraction, the Doppler effect, and interference.

All of these must be taken into account during modeling.

2.2.1. Sound channels

As sound propagates, signal energy decreases with distance. Under certain conditions, phenomena such as refraction and reflection allow sound energy to be channeled into a specific water layer where sound travels significantly greater distances. This layer is known as the underwater sound channel (USC), and it facilitates underwater acoustic communication.

The formation of an underwater sound channel requires a distribution of sound speed in which a minimum propagation speed occurs at a specific depth. The layer where the sound speed is at a minimum is called the axis of the underwater sound channel. Sound energy emitted near the axis of such a channel propagates over greater distances and with lower losses.

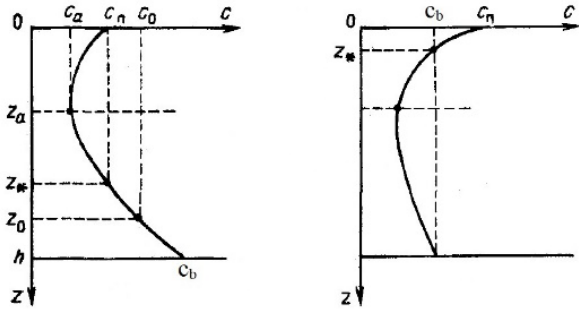


Fig. 1 Sound speed profiles of underwater sound channels [4]

An energy detention coefficient [4] is derived to describe the confinement of sound energy within a sound channel:

$$K_d = \frac{\Omega}{4\pi} \approx \theta_b \approx \sqrt{\frac{2\Delta c_b}{c_b}} \quad (1)$$

where $-\theta_b$ and θ_b are the maximum grazing angles of the rays confined within the sound channel, c_0 is the speed of sound at the source depth (z_0), c_b is the speed of sound at the bottom, and $\Delta c_b = c_b - c_0$ is the change in the speed of sound (Fig. 1). The total energy radiated by the omnidirectional sound source is contained within the solid angle of 4π sr (steradians), while the energy confined within the channel lies within the solid angle Ω bounded by the slopes at angles $\pm\theta_b$.

2.2.2. Winter and summer sound speed profiles

The sound speed profile describes the variation in sound speed with depth. There are two ways to determine the speed of sound in water in situ. The first involves sending an acoustic signal to a receiver at a known distance and measuring the time elapsed between transmission and reception. The second involves measuring the parameters that influence the speed of sound in water, using a CTD (conductivity, temperature, and depth) sensor, and empirically calculating the speed of sound based on a known formula.

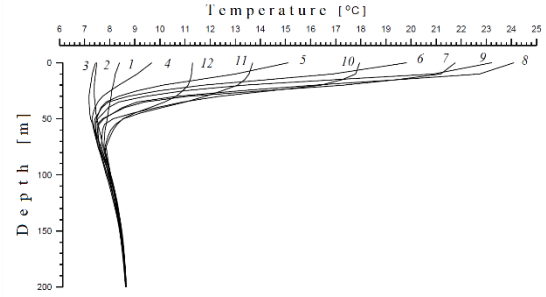


Fig. 2 Seasonal variation in Black Sea water temperature. The numbers on the curves indicate months [5]

In seawater, the speed of sound c is usually in the range of 1450 m/s to 1550 m/s, and depends on the pressure p [MPa] or [bar], salinity S [‰], temperature t [°C], and water acidity: $c = c(p, S, t)$. Since pressure is linearly related to depth, the expression $c = c(z, S, t)$ is also used.

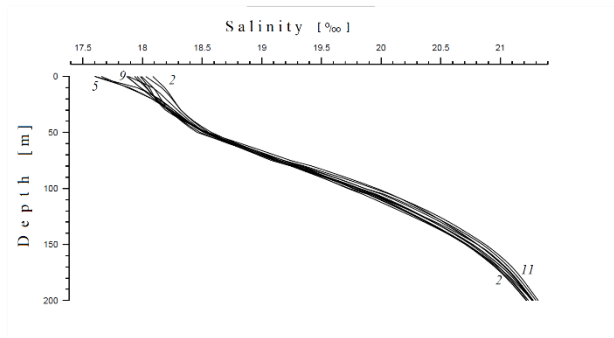


Fig. 3 Seasonal variation in Black Sea water salinity. The numbers on the curves indicate months [5]

Various empirical formulae have been developed to estimate the speed of sound in water. Widely used formulations include the Mackenzie equation, the Del Grosso equation, and the UNESCO equation (TEOS-10).

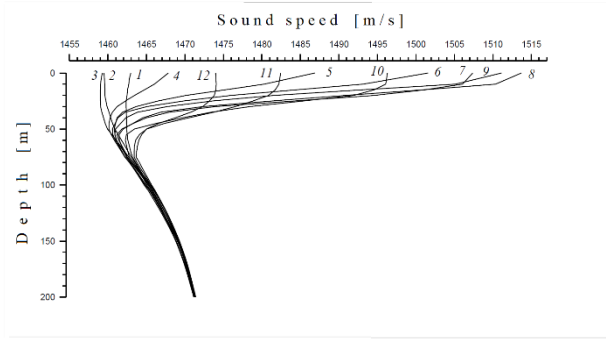


Fig. 4 Seasonal variation in sound speed in the Black Sea. The numbers on the curves indicate months [5]

Seasonal variations in the temperature and salinity of the surface layer of the Black Sea produce corresponding variations in the sound speed profile (Figs. 2–4).

2.3. Mathematical model

To calculate the path of a sound ray through a medium with a known sound speed profile, the source depth (z_h) and initial grazing angle (θ_h) must be specified.

The objective is to calculate sound propagation through a horizontal water layer with a constant sound speed gradient (Fig. 5). Under these conditions, the sound ray follows a circular arc. The ray can therefore be traced by determining the coordinates of the center of curvature (r_{cen} and z_{cen}) and the radius (ρ).

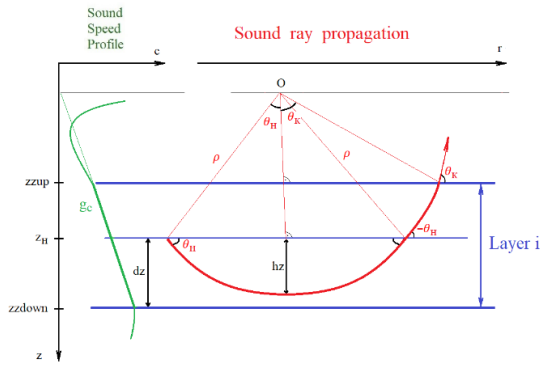


Fig. 5 Propagation of a sound ray through an underwater layer – long case

The required quantities can be determined using invariants. Snell's law gives:

$$\frac{\sin \varphi_2}{\sin \varphi_1} = \frac{c_2}{c_1} = \frac{n_1}{n_2} = \frac{\cos \theta_2}{\cos \theta_1} \quad (2)$$

where θ_1 and θ_2 are the ray grazing angles. It follows that:

$$\frac{c_2}{\cos \theta_2} = \frac{c_1}{\cos \theta_1} = \dots = \frac{c_i}{\cos \theta_i} = \frac{c}{\cos \theta} = c_X \quad (3)$$

where c_X [m/s] is a ray invariant, which remains constant as the ray propagates through different layers. This represents the speed at which the ray would propagate horizontally, rather than the horizontal component of the current velocity ($c_i \cos \theta_i$).

For each layer, the depths (z) and sound speeds (c) at the upper (up) and lower (down) boundaries are known.

Values at intermediate depths can be determined from the sound speed profile (SSP), $c = c(z)$. These data are used to determine the following quantities:

$$g_c = \frac{dc}{dz} = \frac{\Delta c}{\Delta z} = \frac{c_{down} - c_{up}}{z_{down} - z_{up}} \quad (4)$$

where g_c [1/s] is the sound speed gradient, which is constant within the layer.

$$c_{III} = c_h - g_c z_h = c_{up} - g_c z_{up} = c(z) - g_c z \quad (5)$$

where c_{III} [m/s] is the projected surface sound speed, which is constant for the layer. It represents the sound speed at zero depth ($z = 0$) obtained by extrapolating the gradient g_c to the surface.

$$z_{cen} = -\frac{c_{III}}{g_c} \quad (6)$$

where z_{cen} [m] is the nominal depth of the center of ray curvature, which is constant for the layer. At this depth, the extrapolated sound speed would be zero ($c(z_{cen}) = 0$).

Once these constants have been calculated, they can be used to determine the sound speed and other quantities.

$$c(z) = c_{III} + g_c z = g_c (z - z_{cen}) \quad (7)$$

where r_{cen} [m] is determined from the geometry shown in Fig. 5.

$$r_{cen} = r_h - \frac{c_X}{g_c} \sin \theta_h \quad (8)$$

$$\rho = \frac{c_X}{|g_c|} \quad (9)$$

The configuration shown in Fig. 5 is classified as CaseNP, one of the four main model cases. In this case, the initial grazing angle is nonpositive ($\theta_h \leq 0$), and the sound speed gradient is positive ($g_{ci} > 0$). The grazing angle θ increases and may change sign. Two scenarios are distinguished: the short case ($\theta_h < \theta_k < 0$) and the long case ($\theta_h < 0 < -\theta_k < \theta_k$).

For the long case, the calculations are as follows:

$$dz = z_{down} - z_h \quad (10)$$

$$z_k = z_{up} \quad (11)$$

$$\theta_k = +\arccos\left(\frac{|z_{cen} - z_k|}{\rho}\right) \quad (12)$$

$$(r_{cen} - r_h) g_c = -\sqrt{c_X^2 - c_h^2} \quad (13)$$

$$(r_k - r_{cen}) = +\rho \sin \theta_k \quad (14)$$

Analogous calculations are performed for all the cases.

The visualisations use the standard coordinate system for underwater acoustics. The coordinate r denotes horizontal distance from the source, where $r = 0$. The depth coordinate z increases downward, with zero at the water surface.

2.4. Programming implementation

In accordance with the established mathematical model, programs in the C++ language implementing an underwater sound channel (USC) model have been developed. The GNU GCC compiler within the Code::Blocks development environment has been used. A series of classes based on the model proposed by Meyers [6] has been created and used to develop programs that model the USC according to a multipath acoustic model. Each class encapsulates a specific portion of the USC data and enables its storage, processing, and output.

The ray-tracing approach is employed within the USC model. This method takes into account factors such as depth or hydrostatic pressure, temperature, and salinity to derive sound speed profiles. The technique facilitates the prediction of sound propagation, enabling the analysis of signal arrival times, intensity, and other characteristics relevant to underwater acoustic applications. Ray theory is derived from the wave equation by introducing certain simplifying assumptions, and the method is essentially a high-frequency approximation. It is sufficiently accurate for applications involving echo sounders, sonars, and short- to medium-range communication systems [7].

To trace a sound ray, the model calculates the positions of points along the ray and the parameter values at each point. These constitute the output data from the computer model programs and they are saved to output files and subsequently fed into a graphics program for visualisation.

An elementary subproblem of the model involves calculating sound propagation through a horizontal water layer with an approximately constant sound speed gradient. The model implements four main cases and several special cases for this subproblem. Sound ray propagation through an underwater layer with a constant gradient is examined in greater detail in [8].

In general, sound propagation along different rays is analysed, accounting for ray refraction via the ray position function $z = z(r)$ or the ray grazing angle $\theta = \theta(r)$. The received signals (sound intensity level) and power are evaluated by considering two types of losses: reflection (RL) and volume absorption (PL). Travel time (t) can also be calculated.

For each ray, the model determines the path length (s), horizontal distance covered (r), travel time (t), and propagation loss (PL) or sound intensity level (SIL). These quantities are calculated at the receiver location (hydrophone) and can also be evaluated at intermediate points, together with the local grazing angle (θ_i). The calculations proceed layer by layer using the local sound speed profile.

The quantities recorded at each point are as follows: starting point – $\{z_s; r_s = 0; s_s = 0; \theta_s; t_s = 0; SIL_s; PL_s = 0\}$; intermediate points – $\{z_i; r_i; s_i; \theta_i; t_i; SIL_i; PL_i\}$; and end point – $\{z_e; r_e; s_e; \theta_e; t_e; SIL_e; PL_e\}$.

Data on these points are saved in an output file and transferred to a graphics program for visualisation.

3. SOUND SPEED PROFILES AND BLACK SEA DATA

From an acoustic perspective, the Black Sea resembles a typical oceanic environment. Its features include deep water; a summer underwater sound channel with a sound

speed difference of approximately 45 m/s between the channel axis and the seabed; a winter near-surface channel with a rough upper boundary; and a continental slope transitioning into a shelf. However, the Black Sea also differs from other regions. Its salinity ranges from 17 ‰ to 22 ‰ and is approximately one-half to two-thirds that of most ocean waters. Below depths of 125–175 m, the water is saturated with hydrogen sulfide (the so-called "hydrogen sulfide zone") and contains almost no dissolved oxygen [9].

The speed of sound in the Black Sea varies significantly with depth because of variations in temperature, salinity, and pressure. The overall mean is approximately 1487.0 m/s, compared with 1469.8 m/s in the upper 300 m and 1490.2 m/s in the deeper layers (400–2000 m) [10].

Table 1 Mean sound speed profiles of the Black Sea at depths up to 150 m [11]

Z, depth m	P, pressure dbar	Winter (March)		Summer (August)		ΔC m/s
		C m/s	G_c 1/s	C m/s	G_c 1/s	
0	0.0	1457.7		1512.7		55.0
5	5.0	1457.7	-0.0064	1511.2	-0.3955	54.0
10	9.9	1457.6	0.0007	1508.8	-1.0901	51.7
15	14.9	1457.7	0.0255	1500.3	-1.9106	43.1
20	19.9	1457.9	0.0488	1489.8	-2.0476	34.1
25	24.8	1458.2	0.0770	1480.0	-1.7924	25.7
30	29.8	1458.6	0.0737	1472.1	-1.0601	17.7
50	49.7	1459.7	0.0936	1461.9	-0.2356	5.6
75	74.6	1463.0	0.1141	1463.0	0.0758	1.0
100	99.5	1465.4	0.0885	1465.7	0.0932	0.9
125	124.4	1467.4	0.0735	1467.6	0.0716	0.7
150	149.3	1469.0	0.0548	1469.3	0.0533	0.5

The sound speeds for Black Sea depths of up to 150 m presented in Table 1 were calculated by Arkhipkin and Deev [11]. The source data were obtained from a hydrological dataset compiled at the Department of Oceanology, Faculty of Geography, Lomonosov Moscow State University (MSU). The dataset contains more than 90,000 measurements from hydrological stations, grouped into grid cells spanning 16' of longitude and 12' of latitude [11].

The same dataset [11] was used to characterise sound speed at greater depths in the Black Sea.

4. SIMULATIONS AND ACOUSTIC RAY DIAGRAMS

Ocean channels are among the most challenging environments for communication. Acoustic signals are the most suitable means of underwater transmission and require specialised transmitters. However, transmission is affected by absorption, scattering, multipath propagation, the Doppler effect, and other mechanisms. Underwater channel modeling is used to evaluate the spatial configuration of a communication link and the distance traveled by acoustic signals in seawater. Simplifying assumptions are required to reduce the complexity of this assessment [12].

In winter, cooling of the surface layer of the Black Sea produces a surface sound channel with a sound speed profile characterised by a strictly positive gradient (Fig. 6).

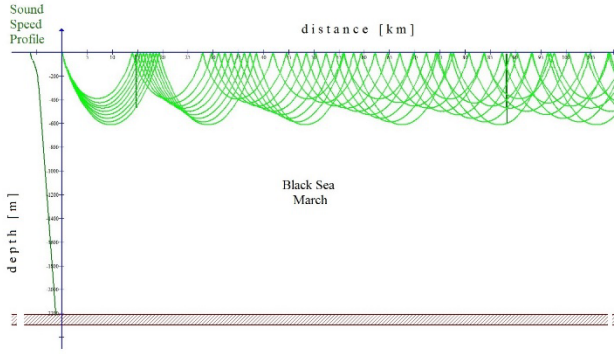


Fig. 6 Acoustic ray diagram for the Black Sea in March, showing a ray beam emitted at approximately 9° 30'

Figure 7 shows the acoustic ray diagram for the Black Sea in March. A beam of rays was traced with initial grazing angles θ_H ranging from -0.2344 to -0.2444 rad and the remaining initial parameters set to $\{z_H = 20.0$ m; $r_H = 0.0$ m; $s_H = 0.0$ m; $\theta_H; t_H = 0.0$ s; $PL_H = 0.0$ dB}. Caustics, where sound rays converge and acoustic energy is concentrated, are visible in the diagram.

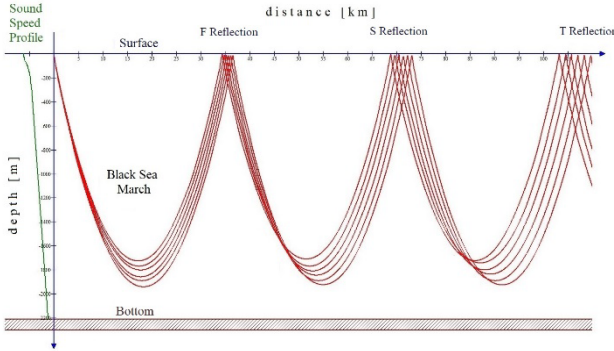


Fig. 7 Acoustic ray diagram for the Black Sea in March, showing a ray beam emitted at approximately 14°

Figure 8 shows the summer acoustic ray diagram for the Black Sea in August. A beam of rays was traced with initial grazing angles θ_H ranging from -0.2379 to -0.2459 rad and the remaining initial parameters set to $\{z_H = 20.0$ m; $r_H = 0.0$ m; $s_H = 0.0$ m; $\theta_H; t_H = 0.0$ s; $PL_H = 0.0$ dB}. The rays bend sharply within the surface layer without reflecting from the surface. This pronounced refraction results from the large magnitude of the sound speed gradient, g_c , in this layer.

Combining multiple relationships in a single diagram allows the parameters of different rays to be compared at a given phase or range, as shown in Fig. 8. Acoustic ray parameters can be classified as cyclic or monotonic. Cyclic quantities vary periodically during sound propagation and include depth (z), angle of incidence (ϕ), grazing angle (θ), and sound speed (c). Monotonic quantities increase or decrease without reversing direction. Examples include path length (s), horizontal distance (r), elapsed time (t), sound intensity level (SIL), and losses (PL , TL).

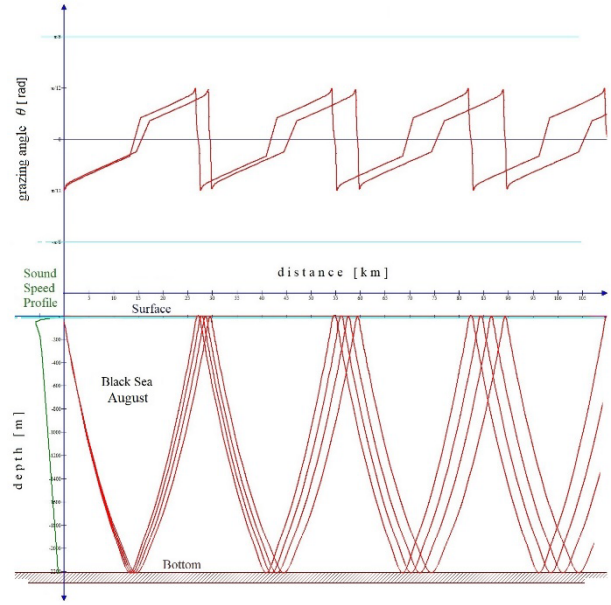


Fig. 8 Combined diagram showing acoustic ray paths and parameters for the Black Sea in August, with a ray beam emitted at approximately 14°

The interdependencies between cyclic parameters form closed curves (Fig. 9). These relationships allow comparisons among rays within a beam, among different beams, and among rays calculated using different sound speed profiles.

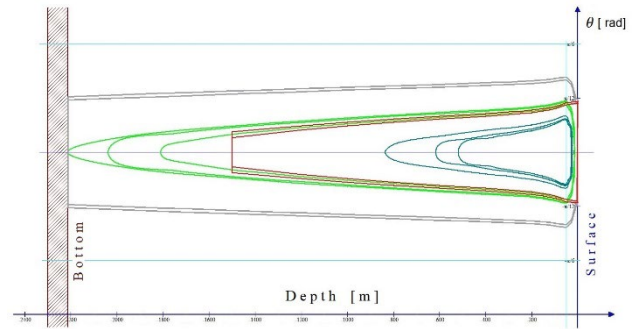


Fig. 9 Sound speed [2]

For a sound signal emitted at $t_H = 0$ s in a known sound field, the wavefront position can be calculated at any subsequent time. The wavefront consists of points at which the acoustic wave has the same phase.

Figure 10 shows the results for a sound ray beam propagating under Black Sea conditions in March (Fig. 6), using computer-modeled sound speed profiles. The beam has an angular width of approximately one degree (0.016 rad = $0^\circ 55' 00''$) and is emitted at an angle of $9^\circ 30'$ relative to the surface. At 10 s after emission, approximately 15 km from the source, the beam undergoes its first surface reflection. The wavefront is nearly straight, with a single deflection (Fig. 10(a)). At 60 s after emission, 88 km from the source, the wavefront is deformed and extends over a horizontal distance of 170.3 m. At a depth of 50 m, this distance corresponds to a travel-time of 0.117 s (Fig. 10(b)).

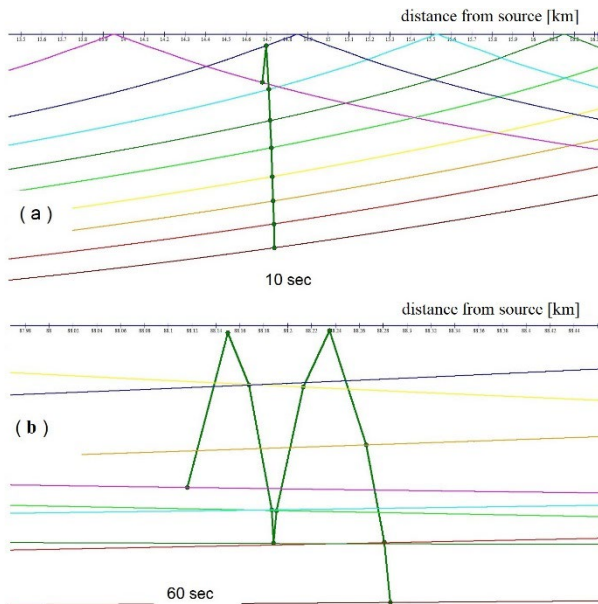


Fig. 10 Sound wavefront at (a) 10 s and (b) 60 s after emission

At a range of approximately 90 km, sound rays following the fastest trajectories lead the slowest rays by approximately one-tenth of a second. The spatial separation of 170.3 m and travel time difference of 0.117 s were obtained for a beam spanning approximately 1° in grazing angle. These differences may increase substantially for wider beams.

Wavefront deformation in underwater sound channels involves bending, stretching, and distortion of the acoustic phase front during propagation. Sound travels along straight paths in homogeneous media, whereas the ocean acts as a dynamic, stratified waveguide. Wavefront visualisation reveals the structure of the sound field and illustrates the associated physical phenomena.

Model calculations and simulations of different media enable wavefront visualisation and the examination of these phenomena.

CONCLUSION

The developed models and computer programs can generate acoustic ray diagrams in real time to characterise underwater communication channels. These results can support improvements in the performance of all types of underwater communication, detection, and localisation systems and inform the design of new systems.

The study focuses on the Black Sea and accounts for local conditions affecting sound propagation, scattering, and attenuation.

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MEASUREMENT OF HYDROPHONE SENSITIVITY IN A SMALL VOLUME WATER-AIR CHAMBER

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Abstract. *A design of a small volume water-air acoustic chamber for hydrophone calibration is described. Analytical results and practical recommendations are presented. The functionality of the chamber has been experimentally demonstrated.*

Key words: *Water-air acoustic chamber, Hydrophone, Calibration, Analytical results*

1. INTRODUCTION

The ocean environment poses substantial challenges to scientific research, economic activities, and technological applications. Electromagnetic waves are strongly attenuated in seawater, whereas acoustic waves can propagate over considerable distances. Low-frequency sound and infrasound generally experience lower attenuation and can therefore travel further. The efficiency of acoustic radiation depends on the size of the radiating aperture relative to the wavelength: lower frequencies correspond to longer wavelengths and generally require larger radiators for efficient emission. These requirements complicate calibration. Accurate calibration is particularly important as civilian and military marine technologies increasingly employ autonomous vehicles and systems for deep-water operations, which require reliable performance at low acoustic frequencies.

Numerous methods are available for the primary and secondary calibration of underwater transducers [1], and the most widely used methods have been standardised [2,3,4]. Advances in electronics and computing have also enabled the development of precise, user-friendly acoustic implementation that facilitates calibration [5]. Nevertheless, calibration and data processing remain time-consuming and labor-intensive. This study considers a modification of the comparison method in which a small-volume chamber is used to determine the sensitivity of a hydrophone under test. The proposed small-volume chamber has a relatively simple design, provides a reported calibration error of less than 1 dB, and is suitable for routine calibration during transducer production. Its characteristic feature is that the sound pressure is created

in the water volume through an air gap, which provides certain advantages described below.

2. FEATURES OF THE ACOUSTIC FIELD IN A SMALL-VOLUME CHAMBER

Calibration in a small-volume chamber is performed when the characteristic chamber dimension L is much smaller than the sound wavelength λ , i.e. $L \ll \lambda$. Under these conditions, the sound pressure can be treated as approximately uniform and independent of position.

To examine these conditions, we consider an auxiliary two-dimensional problem involving the acoustic field in a rectangular domain with perfectly rigid walls.

The boundary conditions, modal pressure distributions, and eigenfrequencies of this field are described below.

■ Neumann boundary conditions

At a stationary, perfectly rigid wall, the normal component of the particle velocity v_n is zero. Consequently, the gradient of the sound pressure p perpendicular to the walls is also zero.

$$\frac{\partial p}{\partial n} = 0 \quad (1)$$

■ Modal sound pressure distribution – eigenmodes

For a rectangular domain with dimensions L_x and L_y , the spatial dependence of each eigenmode is described by cosine functions. The pressure distribution of a given mode is expressed as:

$$p(x|y) = P_0 \cos\left(\frac{n_x \pi x}{L_x}\right) \cos\left(\frac{n_y \pi y}{L_y}\right) \quad (2)$$

where:

P_0 is the maximum pressure amplitude. $n_x, n_y = 0, 1, 2, 3, \dots$ are integer mode indices that specify the number of half-wavelengths along each side.

■ Eigenfrequencies and resonances

The nonzero eigenfrequencies, at which the corresponding modes resonate, are given by:

$$f_{n_x, n_y} = \frac{c}{2} \sqrt{\left(\frac{n_x}{L_x}\right)^2 + \left(\frac{n_y}{L_y}\right)^2} \quad (3)$$

where c is the speed of sound in the medium.

Nonuniform modes exhibit spatial variations in pressure, with alternating maxima and minima.

Reflections from the four walls produce standing-wave patterns that can form a checkerboard distribution of pressure maxima and minima.

When both dimensions are much smaller than the wavelength, $L_x, L_y \ll \lambda$, the field approaches a quasistatic regime. At frequencies well below resonance, spatial variations in the total pressure field are small.

The spatial dependence of individual eigenmodes is described by functions such as

$$\cos\left(\frac{n_x \pi x}{L_x}\right).$$

Although these functions remain spatially nonuniform for nonzero mode indices, the contributions of the corresponding modes are small at frequencies well below resonance. The uniform zeroth mode then dominates, and the pressure oscillates approximately in phase throughout the domain, with no pronounced nodes or antinodes.

This response is dominated by acoustic compliance, with compression and expansion occurring approximately in phase throughout the fluid volume. For an ideal gas under adiabatic conditions, the pressure change associated with a small volume change, such as that produced by a moving piston, is given by:

$$\Delta p = -\gamma P_0 \frac{\Delta V}{V}$$

where γ is the adiabatic index, and P_0 is the equilibrium pressure, and V is the enclosed volume.

Under these conditions, the nonzero eigenfrequencies lie well above the operating frequency. The lowest nonzero eigenfrequency corresponds to a half-wavelength spanning the longest side, $\lambda = 2L_{max}$. Because $\lambda \gg L$, the operating frequency lies well below the first resonance, and resonant standing-wave patterns are not excited.

Consider a rectangular domain of dimensions $L_x \times L_y$, with rigid walls except for the driven boundary at $x = 0$. This boundary oscillates sinusoidally with a normal velocity $v_0 e^{j\omega t}$. The velocity is uniform along y . The medium is water ($c = 1482$ m/s, $\rho = 998$ kg/m³), and the dimensions are $L_x = 0.15$ m and $L_y = 0.25$ m, giving an aspect ratio of 3:5. The pressure is expressed as:

$$p(x) = A_0 + \sum_{n_x=1}^{\infty} A_{n_x} \cos\left(\frac{n_x \pi x}{L_x}\right)$$

where the modal amplitudes, obtained by applying the boundary Green's condition at the radiating surface, are:

$$A_0 = -\frac{jKv_0}{\omega L_x}, \quad A_{n_x} = \frac{-2j\omega\rho v_0}{\left(k^2 - \left(\frac{n_x \pi}{L_x}\right)^2\right) L_x}, \quad n_x \geq 1.$$

Here: $k = \omega/c$ is the wavenumber, and $K = \rho c^2$ is the bulk modulus of elasticity.

Selected results are presented in Fig. 1. The upper left part of the graph shows the first 15 eigenfrequencies. Modes with $n_y = 0$ are highlighted in blue, and the lowest nonzero eigenfrequency in this family is 4940 Hz.

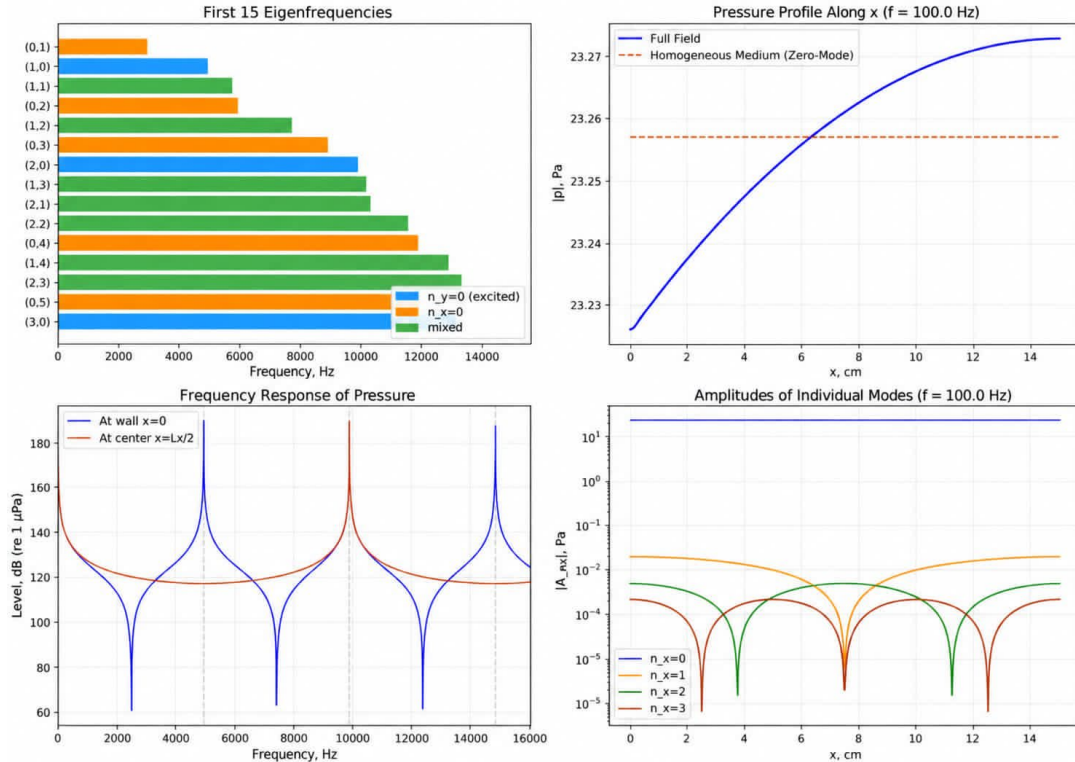


Fig. 1 Eigenfrequencies, pressure profile, frequency response, and modal amplitudes for the rectangular chamber

The upper right part shows the pressure profile along the x-axis at 100 Hz. The blue curve represents the total field, whereas the red dashed line represents the uniform zeroth mode. The calculated spatial variation in pressure is within 0.13 %.

The lower left part shows the frequency response, with resonances at 4940, 9880, and 14820 Hz, corresponding to the modes $(n_x, 0)$.

The lower right part of the graph visualizes the amplitudes of the individual modes on a logarithmic scale.

The amplitude of the zeroth mode exceeds those of the higher modes by three to four orders of magnitude.

Figure 2 illustrates the effects of finite wall stiffness relative to the assumption of perfectly rigid walls. At 100 Hz, the compliance of a 5 cm thick steel wall produces a pressure correction of -0.60 dB. This correction must be considered when an accuracy better than 1 dB is required. For the configuration considered, achieving an accuracy of 0.1 dB requires a wall thickness of at least 10 cm or the use of a ribbed composite structure.

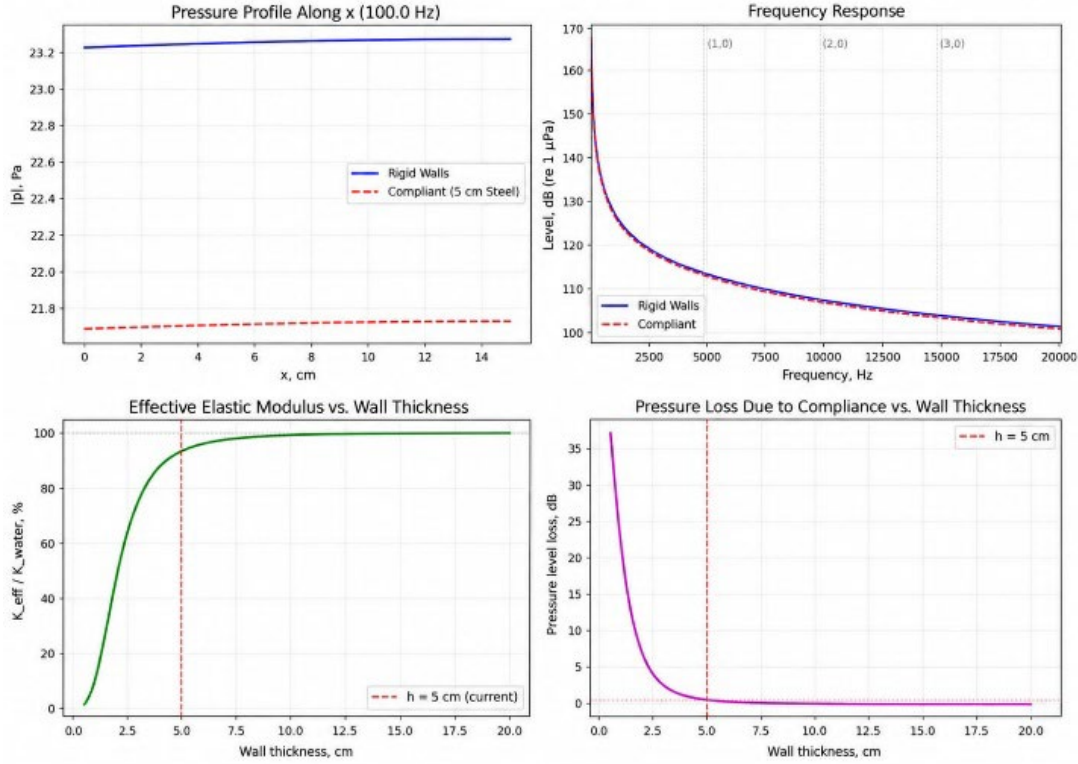


Fig. 2 Effects of wall compliance and wall thickness on pressure and frequency response

3. DESIGN OF A SMALL-VOLUME WATER-AIR CHAMBER

In mass production of hydrophones for underwater acoustic systems, it is important that their sensitivity be measured with satisfactory accuracy. Moreover, the measurement should not be labor-intensive, should not require complex preparatory activities, and at the same time should be performed in an environment that is as close as possible to the working one. Therefore, pistonphones [5], although they provide the necessary accuracy, are not always suitable, especially since different types of hydrophones require appropriate coupling devices.

Hydroacoustic measurement tanks are large, complex facilities with substantial maintenance costs. For this reason, the present work proposes a hybrid design of a small-volume chamber, shown below. It is based on the relations and calculations made in the previous section. The essence of the idea can be explained with Fig. 3 [6,7,8].

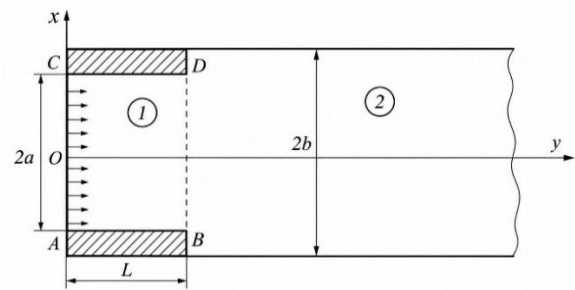


Fig. 3 Waveguide geometry used in the analysis

Consider an infinite waveguide that is symmetric about the y-axis. The walls AB and CD are perfectly rigid, and a radiating piston occupies the boundary segment AC. The velocity potential Φ_1 in region 1 can be represented in two equivalent forms:

$$\Phi_1 = \sum_{m=0}^{\infty} \cos \frac{m\pi}{a} x \left\{ A_m \exp(j\alpha_m y) + B_m \exp[-j\alpha_m (y-L)] \right\} \quad (4)$$

$$\Phi_1 = \sum_{m=0}^{\infty} \cos \frac{m\pi}{a} x \left\{ a_m \cos \alpha_m y + b_m \sin \alpha_m y \right\} \quad (5)$$

where $\alpha_m = \left[k^2 - \left(\frac{m\pi}{a} \right)^2 \right]^{1/2}$, and a_m , b_m , A_m , and B_m are complex coefficients.

Using Eq. (5), the acoustic intensity, or power flux density, is obtained as

$$W_y = \frac{1}{4} j \omega \rho \alpha_m (a_m b_m^* - a_m^* b_m)$$

when

$$\alpha_m^* = \alpha_m$$

i.e., when α_m is real, and when

$$\alpha_m^* = -\alpha_m$$

i.e., when α_m is purely imaginary. The asterisk (*) denotes complex conjugation.

These representations satisfy the Helmholtz equation and the boundary conditions within each domain while retaining sufficient freedom to satisfy the matching conditions between regions 1 and 2.

The regime of interest occurs when the wavelength λ is much larger than the characteristic dimension L . In this limit, the field in region 1 can be analysed by solving the Laplace equation for the velocity potential Φ_1 subject to the corresponding boundary conditions.

$$\Phi_1 = \sum_{m=0}^{\infty} \cos \frac{m\pi}{a} x \left(A_m \operatorname{ch} \frac{m\pi}{a} y + B_m \operatorname{sh} \frac{m\pi}{a} y \right) \quad (6)$$

Applying the same procedure gives

$$w_y = \frac{1}{4} j \omega \rho \frac{m\pi}{a} (B_m^* A_m - A_m^* B_m)$$

The expression for w_y is real, indicating that an acoustic power flux can also occur in this case.

These considerations, together with the relations derived in the preceding section, lead to the idea that the small-volume chamber should consist of two sections (chambers) arranged one above the other, as shown in Fig. 4.

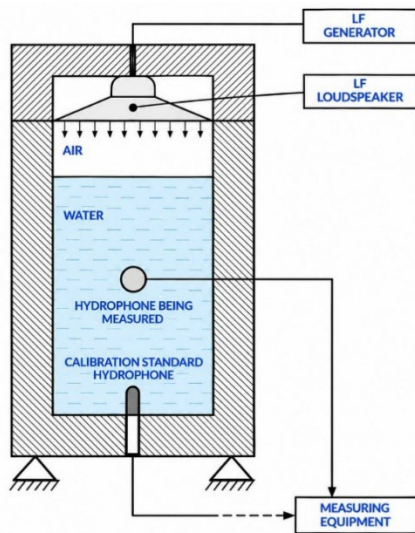


Fig. 4 Schematic of the water-air chamber and comparison measurement arrangement

A low-frequency loudspeaker generates the acoustic field in the water-filled section through the air-filled

section above it. The dimensions of both sections satisfy the small-volume conditions discussed above. The loudspeaker is mounted in a lid that is securely fastened when closed. One or more hydrophones under test are suspended from special holders attached to the lid and immersed in the water. Their exact positions are not critical because the field is approximately uniform; the residual spatial variation depends on the chamber dimensions and wall thickness.

Hydrophone sensitivity is measured using the comparison method. The pressure sensitivity is defined by:

$$M(f) = \frac{U(f)}{p(f)} \quad (7)$$

where:

$M(f)$ is the hydrophone pressure sensitivity, in V/Pa;
 $U(f)$ is the hydrophone output voltage, in V; and
 $p(f)$ is the acoustic pressure acting on the hydrophone, in Pa.

The acoustic field in the water-filled section is excited through the water surface. From the air side, the water surface can be approximated as an acoustically rigid boundary.

The main advantages of the design shown in Fig. 4 are as follows:

- Measurements were performed in water, the operating medium of the hydrophone, avoiding the corrections required for measurements in air.
- Several hydrophones, for example three, can be measured simultaneously. They are suspended from the lid, with their connecting cables routed between the lid and the chamber body.
- The reported measurement error is less than 1 dB, which is adequate for the intended operating conditions of the hydrophones.
- The measurement procedure is convenient and rapid.

Before measurement, the hydrophones must reach thermal equilibrium with the water. Appropriate precautions must also be taken to prevent cavitation during the measurements.

A chamber of this design was tested and used at the former Institute of Radio Engineering Equipment in Veliko Tarnovo during the production of active and semi-passive transducers of the sound-cell type. Its functionality was confirmed in practical use.

4. CONCLUSION

Established methods and standards provide a basis for calibrating underwater transducers. However, advances in hydroacoustic technology for ocean resource exploration and defense require suitable instruments and calibration methods for low-frequency transducers used at greater depths and over longer distances. This study proposes a small-volume water-air chamber for low-frequency hydrophone measurements. Modeling and calculations indicate that the chamber generates an acoustic field suitable for these measurements. The chamber has also been tested in practice, confirming its functionality.

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INTERDEPENDENCE OF NOISE LEVEL MEASUREMENT RESULTS OBTAINED USING INSTRUMENTS OF DIFFERENT ACCURACY CLASSES

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Abstract. *This paper compares noise-level measurements obtained with instruments of different accuracy classes. Reference measurements were performed using a Class 1 sound level analyser and comparative measurements using a Class 2 sound level meter. Simultaneous measurements were conducted under field conditions during operation of a water-treatment plant and drilling rigs, and during residual-noise measurements. Two residual-noise conditions were considered: steady noise and noise intermittently affected by a distant source. Linear regression models for correcting Class 2 results were developed from paired measurements. The coefficients of determination were 0.9976 and 0.9988, indicating a very strong linear relationship. The proposed approach enables estimation of noise levels equivalent to Class 1 measurements, provided that the correction function is established beforehand and applied only under defined conditions.*

Key words: *Noise, Measurement, Accuracy classes, Sound level meter, Linear regression, Correction*

1. INTRODUCTION

Measuring the noise level is the basis for assessing the state of the living and working environment, identifying dominant sources and planning appropriate protection measures. The reliability of the obtained results depends not only on the characteristics of the measuring instrument, but also on the mode of operation of the source, the duration of the measurement, the position of the microphone, residual noise, meteorological conditions and the applied data processing procedure. The SRPS ISO 1996-2 standard indicates that the total measurement uncertainty includes contributions from the instrument, operating and meteorological conditions, and residual sound [1].

Sound level measuring instruments are classified, according to the IEC 61672-1 standard, into two performance classes: Class 1 and Class 2 [2]. Instruments of both classes are based on the same principles of measurement, but differ in their permissible limits of deviation, frequency range and range of operating conditions. The stricter acceptance limits of Class 1 instruments make them suitable for precise measurements and procedures in which it is necessary to minimise the

instrumental component of measurement uncertainty. Class 2 instruments have wider acceptance limits, but due to their lower cost, simpler use and greater availability, they can play a significant role in control, indicative and repeated field measurements [3].

The need for more economical measurement systems is especially pronounced when a large number of measurement points need to be covered or long-term monitoring is to be carried out. Therefore, numerous studies have been focused on examining the agreement between the results of reference instruments and more accessible measurement systems. Kardous and Shaw [4] examined a number of applications and devices in relation to the Class 1 reference measurement system in the range of 65 to 95 dB. In the case of individual configurations, small average deviations were obtained, while at the same time significant differences between the devices were determined, due to the characteristics of the microphone, hardware and signal processing method. These results show that the reliability of a more economical system cannot be assumed based on its declared purpose, but must be experimentally verified in relation to a reference instrument [4].

Risojević et al. [5] developed an economical measurement system for continuous noise level monitoring and compared its results with those obtained using a Class 1 instrument. After calibration based on polynomial adjustment of the results in the range of 50 to 100 dB, a mean difference of less than 2 dB was achieved. Research has shown that with appropriate calibration and processing, the agreement with the reference instrument can be significantly improved, but also that such systems remain intended primarily for informative monitoring, and not for measurements whose results have formal metrological or legal significance [5].

The importance of the correction of measurement results was also confirmed in the research of Aumond et al. [6], in which a field calibration procedure for low-cost devices was developed. After the correction was applied, a comparison of eight devices with a Class 1 instrument at six control points yielded an average deviation of -0.6 ± 1.2 dB(A). The authors pointed out that calibration is one

of the key prerequisites for increasing the usability of data obtained by more accessible measurement systems [6].

The latest research by Sasindran et al. [7] showed that deviations from the results of a Class 1 instrument can depend on the type of measuring system, the specific device, the sound level, the frequency and the applied correction. Generalised linear models were used to analyse these impacts. It was established that the correction can improve agreement in certain conditions, but that its effectiveness is not equal for all devices, frequencies and types of sound signal [7].

Wider tests of economical systems for noise level measurement also confirm that their reliability depends to a large extent on the specific measuring chain and calibration method. Murphy and King [8] conducted 1,472 tests on 100 mobile devices and showed significant differences between individual configurations, with only some solutions achieving deviations comparable to those of professional measurement systems. In a follow-up study, Kardous and Shaw [9] showed that the application of a calibrated external microphone can significantly improve the accuracy and repeatability of the results. Celestina et al. [10] tested a similar measurement system according to the requirements of international standards and showed that the combination of a suitable external microphone and software application can satisfy most of the tested requirements of Class 2 according to IEC 61672.

The development of low-budget systems is not limited to mobile phones. Quintero et al. [11] developed a cost-effective noise measurement system and achieved good agreement with a Class 1 instrument under laboratory and field conditions, with deviations of approximately ± 0.5 dB for L_{Aeq} . An overview of the development of wireless acoustic sensor networks shows that modern systems are increasingly based on a compromise between price, spatial density of measurement sites and required accuracy [12]. The newer EcoDecibel system also showed a high correlation with the results of Class 1 and Class 2 instruments during laboratory and field tests [13], confirming the possibility of applying more economical systems for long-term noise monitoring provided that their measurement characteristics have been established experimentally.

The studies discussed above are mainly related to mobile applications, sensor nodes and other economical measurement systems. In contrast, the subject of this paper is a comparison of two dedicated instruments for noise level measurement, which belong to different accuracy classes. Comparative measurements were carried out simultaneously, in real field conditions, with stable and occasionally disturbed residual noise, as well as during the operation of water-treatment plants and drilling rigs. This includes different sources and levels of noise, from low ambient noise levels to high levels characteristic of industrial equipment.

The aim of the work is to determine the degree of interdependence of the measurement results obtained by Class 1 and Class 2 instruments, quantify their mutual deviations and form regression models to estimate the level

that would be obtained by a reference instrument of Class 1 based on the results of a Class 2 instrument. The obtained models refer to the tested instruments, the analysed range of noise levels and the conditions in which the measurements were carried out. Their application does not change the metrological class of a Class 2 instrument, but represents an empirical procedure for correcting its results under defined conditions.

2. MEASURING EQUIPMENT AND TESTING METHODOLOGY

2.1. Measuring equipment

For comparative testing, two dedicated sound level measuring instruments belonging to different performance classes according to the IEC 61672-1 standard were used. A Class 1 sound analyser was used as a reference instrument, while a Class 2 sound level meter was used as a comparison instrument. In the remainder of this paper, the instruments are designated K1 and K2 to avoid using manufacturer names and commercial designations.

The reference instrument K1 enables immediate determination of the A-weighted equivalent sound level $L_{Aeq,T}$ during the selected time interval. This quantity represents the level of a time-invariant sound that, in the observed interval, would have the same sound energy as a real, time-varying sound. The K1 instrument has an internal memory and the ability to save results and time records of measurements.

The comparison instrument K2 is equipped with a condenser microphone with a diameter of 1/2 inch. Its frequency range is from 31.5 Hz to 8 kHz, while the nominal dynamic measurement range is from 30 to 130 dB. Display resolution is 0.1 dB. The instrument supports A-weighting and FAST and SLOW time weightings, with time constants of 125 ms and 1 s, respectively. Declared operating conditions include a temperature range of 0 °C to 40 °C and a relative humidity of less than 90%.

Unlike the K1 instrument, the K2 instrument does not have an internal memory for saving results. Therefore, it was connected to a laptop via a USB interface during the measurement. An appropriate software package was used for continuous recording and storage of current sound level values. Subsequent analysis of the records revealed that the interval between successively recorded values was 0.5 s.

Both microphones were fitted with wind protection, in accordance with the requirements for outdoor noise measurement. The microphones of instruments K1 and K2 were placed directly next to each other, at the same height and approximately the same distance from the observed source. This arrangement reduced the influence of spatial inhomogeneity in the sound field and ensured, as far as practicable, that both instruments recorded the same sound event.

Table 1 Basic characteristics of the applied measuring instruments

Characteristic	Instrument K1	Instrument K2
Class according to IEC 61672-1	Class 1	Class 2
Role in the study	Reference instrument	Comparative instrument
Basic result	$L_{Aeq,T}$	Sound level time series
Frequency weighting	A	A
Time weightings	FAST/SLOW and integration measurement	FAST/SLOW
Frequency range	According to Class 1 specifications	31.5 Hz - 8 kHz
Nominal measuring range	According to the instrument specification	30 – 130 dB
Display resolution	According to the instrument specification	0.1 dB
Data storage	Internal memory	Computer connected via USB interface
Recording interval used in this study	According to the selected measurement mode	0.5 s

2.2. Calibration of the measuring system

Before the beginning of the field measurements, a check of the measuring systems was carried out using an acoustic calibrator. The calibration signal had a sound pressure level of 94 dB at a frequency of 1 kHz. The microphone was placed in the appropriate calibrator coupler, which ensured stable and repeatable acoustic excitation.

The K1 instrument was used as a reference instrument with a valid metrological certificate, while the K2 instrument was adjusted to the value of the calibration signal before the start of the measurement. The check included the complete measuring chain of the K2 instrument: microphone, converter and processing part of the instrument, USB communication, computer and software package for recording results.

The calibration check verified the sensitivity and stability of the K2 instrument before comparative measurements without changing its metrological class. The instrument's class is determined by its design and compliance with the requirements of the IEC 61672-1 standard, while a field test determines whether the measuring system displays the expected value in response to the reference signal at the time of use.

After the calibration check, both instruments were set to A-weighting and the corresponding time modes. Before each comparative recording, the start times and measurement durations were aligned so that the results referred to the same time interval. Special attention was paid to the stability of the USB communication and continuous data storage of the K2 instrument, because the loss of individual records can affect the determination of the representative level and the subsequent regression analysis.

The procedure for checking and using the instruments complies with the general requirements of the ISO 1996-2 standard for measuring noise in the environment. The standard provides for checking the measuring system with

an acoustic calibrator immediately before and after a series of measurements.

2.3. Comparative measurement procedure and data processing

Comparative measurements were carried out in real field conditions, with different noise levels and characteristics. The measurements included residual noise, relatively stable industrial plant noise, and variable noise from a dominant industrial source. In this way, a set of data was formed that includes a wide range of sound levels and different operating modes of the source.

The Class 1 reference instrument and the Class 2 comparison instrument were positioned very close to each other. The microphones were exposed to the same sound field, and the measurements were carried out simultaneously over identical time intervals. This reduced the influence of source variability and external conditions on inter-instrumental deviations. Before measurements began, an acoustic check of the measuring chains was performed using the appropriate calibrators, at a reference sound pressure level of 94 dB and a frequency of 1 kHz.

A Class 1 instrument was used to directly determine the equivalent A-weighted sound level $L_{Aeq,T}$. A Class 2 instrument was used to continuously record instantaneous A-weighted sound levels, with a sampling interval of 0.5 s. The recorded data were transferred to a computer and processed for the same time intervals for which reference values were obtained with a Class 1 instrument.

For a series of N instantaneous levels $L_{A,i}$, registered by a Class 2 instrument, the equivalent sound level is determined using the expression:

$$L_{Aeq,T}^{(2)} = 10 \log_{10} \left[\frac{1}{N} \sum_{i=1}^N 10^{L_{A,i}/10} \right] \quad (1)$$

where $L_{Aeq,T}^{(2)}$ is the equivalent A-weighted level obtained on the basis of Class 2 instrument records, and $L_{A,i}$ is the individual sound level value at the i -th sampling moment.

Such energy averaging provides a physically justified comparison with the value $L_{Aeq,T}^{(1)}$, which is directly determined by a Class 1 instrument.

A pair of values was formed for each measurement interval:

$$\left(L_{Aeq,T}^{(2)}, L_{Aeq,T}^{(1)} \right) \quad (2)$$

The values obtained by the instrument of Class 2 were treated as the independent variable x , while the results of the reference instrument of Class 1 represented the dependent variable Y . The interdependence of the results was described by a linear regression model:

$$Y = ax + b \quad (3)$$

where a is the slope of the regression line, and b is the intercept on the ordinate. The parameters of the model were determined by the method of least squares. The slope of the regression line was used to estimate the proportional deviation of the measurement scales, while the intercept value was considered as an indicator of an approximately constant component of the deviation between the results of the two instruments.

The strength of the linear association was evaluated by the coefficient of determination R^2 . In addition to the regression analysis, the difference was determined for each pair of measurements:

$$\Delta L_i = L_{Aeq,T,i}^{(2)} - L_{Aeq,T,i}^{(1)} \quad (4)$$

where a positive value of ΔL_i indicates that the Class 2 instrument registered a higher level than the reference instrument. The sign, magnitude and variation of these deviations were analysed in relation to the noise level and characteristics of the observed source.

In order to examine the impact of residual noise, two sets of data were created. In the first set, the result obtained with relatively stable residual noise was used,

while in the second set, the lowest value corresponded to variable residual noise, occasionally disturbed by the effect of a distant source. Other pairs of results related to more stable industrial sources and were common to both sets. A linear regression model was created separately for each set.

The procedure defined in this way enables the evaluation of the interdependence of the results of instruments of different accuracy classes, the identification of systematic deviations and the consideration of the possibility of applying the regression equation for the correction of the results obtained by the instrument of Class 2.

3. RESULTS AND DISCUSSION

3.1. Comparative display of measurement results

Comparative measurements included eight characteristic modes of industrial noise and two variants of residual noise. For each time record of a Class 2 instrument, the equivalent A-weighted sound level was calculated by energy averaging the instantaneous values registered at 0.5 s intervals. The obtained values were compared with equivalent levels directly measured by a Class 1 reference instrument.

Table 2 shows the number of samples N , the results of both instruments and their mutual difference: $\Delta L = L_{Aeq,T}^{(2)} - L_{Aeq,T}^{(1)}$.

The Class 2 instrument gave higher values in all analysed cases. The differences ranged from 0.5 to 4.5 dB. The biggest deviation was recorded under stable residual noise conditions, i.e. at the lowest sound levels. For industrial sources, the deviations were between 0.5 and 2.7 dB, without a simple monotonic dependence on the total noise level.

Table 2 Comparative results of noise level measurements

Measurement conditions	Distance [m]	N	Class 2 $L_{Aeq,T}$ [dB(A)]	Class 1 $L_{Aeq,T}$ [dB(A)]	ΔL [dB]
Residual noise - stable	-	137	33.4	28.9	4.5
Residual noise - variable	-	163	34.7	32.5	2.2
Industrial source 1	50	173	45.9	45.4	0.5
Industrial source 2	50	107	46.2	45.0	1.2
Industrial source 1	40	178	49.9	48.6	1.3
Industrial source 1	30	172	54.1	51.4	2.7
Industrial source 1	20	133	58.8	56.1	2.7
Industrial source 1	3	266	70.5	68.6	1.9
Industrial source 2	3	182	86.5	85.2	1.3
Industrial source 2	0.5	119	100.4	99.6	0.8

The results indicate that the difference between the instruments is not constant across the entire observed measurement range. Therefore, the application of a single additive correction would not sufficiently describe their

mutual relationship. This fact justifies the application of linear regression analysis, which simultaneously takes into account the proportional and approximately constant components of the inter-instrumental deviation.

The effect of regression correction is summarised in Table 3.

Regression correction reduced the mean absolute error by approximately 56% in model v_1 and 62% in model v_2 . At the same time, the largest individual difference

between the corrected and reference results was also reduced. The obtained indicators confirm that the regression approach significantly improves agreement between the results, although it does not completely eliminate deviations in each individual measurement.

Table 3 Indicators of deviation before and after regression correction

Dataset	Indicator	Before correction [dB]	After correction [dB]
Stable residual noise – model v_1	Mean absolute error	1.87	0.82
	RMSE	2.20	1.03
	Maximum absolute deviation	4.47	1.85
Variable residual noise – model v_2	Mean absolute error	1.62	0.61
	RMSE	1.78	0.71
	Maximum absolute deviation	2.70	1.25

3.2. Regression analysis

Linear regression analysis was used to quantitatively describe the interdependence of the results of instruments of different accuracy classes. The equivalent sound level calculated by energy averaging the Class 2 instrument recordings was used as the independent variable x , while the result obtained using the Class 1 reference instrument was used as the dependent variable Y . The parameters of the regression models were determined by the method of least squares.

Two sets of nine pairs of results were analysed. The sets contained eight common measurements of industrial noise, while the lowest value differed depending on the character of the residual noise. In the first set, stable residual noise was used, and in the second, variable residual noise with the occasional influence of a distant source.

A regression model was obtained for a data set with stable residual noise:

$$Y = 1.0274x - 3.5331 \quad (5)$$

with the coefficient of determination: $R^2 = 0.9976$ (Fig. 1).

The regression slope of 1.0274 shows that the relationship between the results of the two instruments cannot be described only by a constant additive correction. A slope value greater than unity, together with a negative intercept on the ordinate, indicates the existence of proportional and constant components of the inter-instrumental deviation. In the observed measurement range, the regression equation corrects the results of the Class 2 instrument downwards, whereby the relative influence of the correction is more pronounced at lower sound levels.

The value of $R^2 = 0.9976$ shows that the regression model explains 99.76% of the variability in the results of the reference instrument. However, the high coefficient of determination primarily confirms the very strong linear association of the results. It is not in itself sufficient proof of their mutual agreement. Therefore, the model should be evaluated together with individual deviations and error indicators.

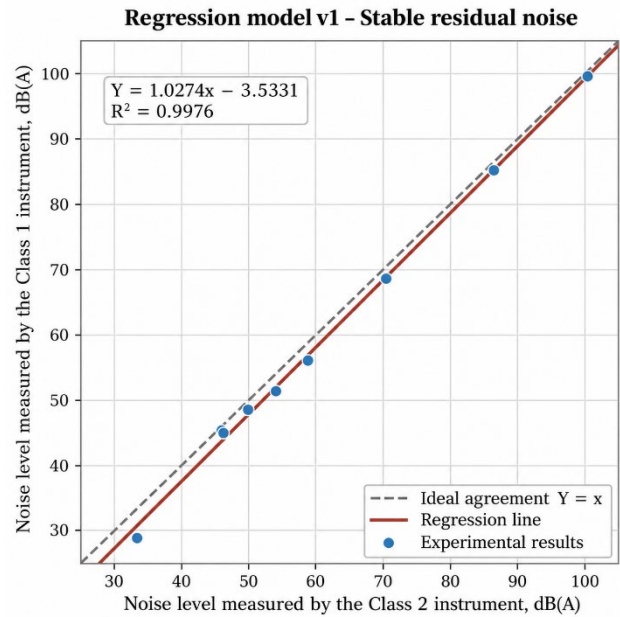


Fig. 1 Interdependence of Class 1 and Class 2 measurement results for model v_1

With model v_1 , the mean absolute error after correction was 0.82 dB, while the root mean square error was 1.03 dB. The largest absolute deviation of the corrected value from the reference result was 1.85 dB and was recorded at the lowest sound level. This result indicates that the reliability of the correction is somewhat lower in the area close to the lower limit of the measurement range used.

For the data set with variable residual noise, the following model was obtained:

$$Y = 1.0105x - 2.2562 \quad (6)$$

with the coefficient of determination: $R^2 = 0.9988$ (Fig. 2).

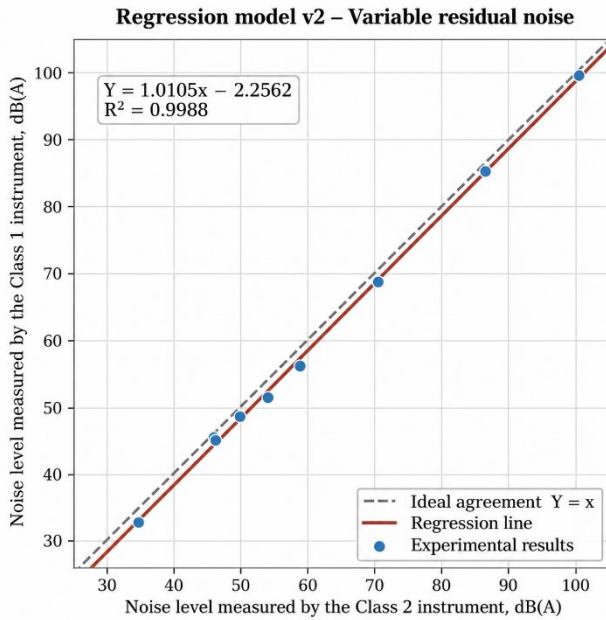


Fig. 2 Interdependence of Class 1 and Class 2 measurement results for model v_2

The regression slope of 1.0105 is closer to unity than that of the v_1 model, indicating greater agreement between the measurement scales in the second data set. The negative intercept shows that in this case too, a downward correction of the results of the Class 2 instrument is required. The obtained R^2 value shows that the model explains 99.88% of the variability of the results of the reference instrument.

After the v_2 model was applied, the mean absolute error was reduced to 0.61 dB, and the root mean square error was reduced to 0.71 dB. The maximum absolute deviation was 1.25 dB. According to these indicators, model v_2 achieved slightly better agreement between corrected and reference values than model v_1 .

On the regression diagrams, in addition to the experimental points and the regression line, the line of ideal agreement $Y = x$ is shown. The position of the experimental points in relation to this line enables direct observation of the systematic deviation of the Class 2 instrument, while the distance of the regression line from the line $Y = x$ shows the size of the modelled correction in the observed measurement range.

The results of both models confirm the pronounced linear interdependence of the measured levels in the range from approximately 30 to 100 dB(A). Regression correction significantly reduces total deviations, but the resulting equations should be viewed as calibration models specific to the analysed measurement systems and the measurement conditions used. Their direct application to other Class 2 instruments is not justified without first conducting appropriate comparative measurements.

Due to the small number of pairs of results and the fact that the same data were used for both determination and evaluation of the model, the presented indicators represent a measure of the goodness of fit to the existing data. Independent validation of the proposed regression equations requires additional measurements that are not used to determine the model parameters.

3.3. Deviation analysis and practical application of correction

Table 2 shows that in all analysed cases the Class 2 instrument registered a higher noise level than the reference instrument of Class 1. The mean deviation before correction was 1.87 dB for the set with stable residual noise and 1.62 dB for the set with variable residual noise. The positive sign of all individual differences indicates the presence of a systematic component of the deviation.

The largest deviation of 4.47 dB was recorded under stable residual noise conditions, i.e. at the lowest analysed sound level. Under variable residual noise conditions, the deviation was 2.19 dB, while for industrial sources the differences were between 0.52 and 2.70 dB. The obtained results show that the size of the deviation does not depend only on the accuracy class of the instrument, but also on the level, temporal variability and spectral characteristics of the observed noise.

After the application of the regression models, the mean value of the signed residuals was practically equal to zero, which is the expected consequence of the application of the least-squares regression with an intercept. Therefore, the mean absolute error, the root mean square error and the largest absolute deviation are more relevant for the evaluation of the correction quality.

The residual of the corrected value is defined by the expression:

$$e_i = \hat{Y}_i - Y_i \quad (7)$$

where $\hat{Y}_i$ is the value estimated by the regression model and Y_i is the result of the Class 1 reference instrument.

For model v_1 , the residuals ranged from approximately -1.75 to 1.85 dB, while for model v_2 they ranged from approximately -1.25 to 1.07 dB. The sign of the residuals changed in the observed measurement range, which shows that the model does not lead to one-sided overestimation or underestimation of all corrected results. Given the small number of measurements, however, it is not possible to reliably assess the shape of the distribution of the residuals or possible heteroskedasticity.

Application of the v_1 model reduced the mean absolute error from 1.87 to 0.82 dB, while with the v_2 model it was reduced from 1.62 to 0.61 dB. The maximum absolute deviation was reduced from 4.47 to 1.85 dB in the first model, and from 2.70 to 1.25 dB in the second model. This confirmed that the regression correction improves the mutual agreement of the results compared to the uncorrected values.

The practical application of the correction involves entering the value measured by the Class 2 instrument as the variable x in the corresponding regression equation. The obtained value $\hat{Y}$ represents an estimate of the level that, under the same conditions, would be registered by a reference instrument of Class 1. The choice of model depends on the character of the residual noise and the conditions in which the measurement was performed.

The regression equations should only be applied within the range of noise levels covered by the comparative measurements, approximately from 30 to 100 dB(A). Their extrapolation beyond this range is not justified because the behaviour of the measuring system at very low or very high levels has not been experimentally verified. Special caution

is needed in the area of low noise levels, where the largest inter-instrumental deviation is observed and where the influence of the instrument's own noise, resolution and boundary characteristics is relatively more pronounced.

The obtained correction equations refer exclusively to the analysed pair of measurement systems. They cannot be directly applied to another Class 2 instrument, even when it is of the same type, without a prior comparative check with a reference instrument. Changing the microphone, calibrator, settings, data acquisition software, or time processing mode can affect the parameters of the regression model.

Regression correction does not change the metrological class of the instrument. After correction, a Class 2 instrument does not become a Class 1 instrument, nor can the corrected results be automatically used without additional assessment of measurement uncertainty in procedures in which the application of a Class 1 instrument is prescribed. The proposed procedure is primarily suitable for internal, indicative and control measurements, monitoring changes in noise level and planning more detailed measurements with reference equipment.

To preserve the reliability of the model, comparative measurements should be repeated periodically, especially after instrument servicing, replacement of the microphone or calibrator, or prolonged use, and whenever unusual deviations are observed. In this way, the regression model can be a practical tool to improve the usability of the results of a Class 2 instrument, while maintaining a clear distinction between the corrected estimate and the measurement made using an instrument of a higher accuracy class.

4. CONCLUSION

The paper analysed the interdependence of noise level measurement results obtained through the simultaneous use of Class 1 and Class 2 instruments. The comparative measurements included different modes of operation of industrial sources, as well as two characteristic states of residual noise. The obtained results showed a high degree of correlation between the measured values, but also the existence of systematic inter-instrumental deviations.

In the observed conditions, the Class 2 instrument showed higher noise levels than the Class 1 instrument in all analysed cases. As the size of the deviation was not constant across the entire tested range, the application of a single additive correction was not assessed as appropriate. Therefore, linear regression models were created, which can correct the results of the Class 2 instrument and bring them closer to the reference values obtained by the Class 1 instrument.

Applying the regression correction reduced the mean absolute error from 1.87 dB to 0.82 dB for the first data set, and from 1.62 dB to 0.61 dB for the second data set. This confirmed that the regression approach can significantly improve the mutual agreement between the results of the two instruments.

The resulting models refer exclusively to the tested instruments, the analysed noise level range and the applied measurement conditions. The correction does not change the declared accuracy class of the instrument, nor can it replace the use of a Class 1 instrument when it is prescribed by standards or legal requirements. Nevertheless, this approach can be useful for indicative, control and periodic measurements, with previously determined and regularly checked interdependence of the results of specific instruments.

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ACOUSTIC DIAGNOSTIC METHOD FOR EARLY DETECTION OF INCOMPLETE COMBUSTION IN INDIVIDUAL CYLINDERS OF GASOLINE ENGINES WITH INDIRECT FUEL INJECTION

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Abstract. Existing diagnostic systems can detect misfire events in individual cylinders of gasoline internal combustion engines. However, an experienced diagnostician can often recognize irregular or incomplete combustion from the exhaust sound before a sufficiently pronounced misfire is detected and stored as a diagnostic trouble code. This phenomenon may be particularly noticeable in bi-fuel gasoline/LPG vehicles, where operation on gaseous fuel can place higher electrical demands on the ignition system. The proposed method combines the crankshaft position sensor signal with the acoustic signal measured at the exhaust outlet. The CKP signal is used as a rotational and temporal reference, while diagnosis is performed primarily from the time-domain acoustic waveform. A vehicle-specific calibration procedure, performed by deliberately disabling a known cylinder, compensates for the effective delay introduced by the exhaust system and measurement chain and allows an abnormal acoustic event to be associated with the corresponding cylinder. The method is intended as a low-cost, non-invasive supplement to conventional onboard diagnostics and can be implemented using a conventional two-channel oscilloscope and microphone.

Key words: Acoustic diagnostics, Incomplete combustion, Misfire, LPG, Crankshaft position sensor, Exhaust sound

1. INTRODUCTION

The development of diagnostic equipment for passenger vehicles has closely followed the increasing complexity of automotive powertrains and electronic control systems. Early engine diagnostics relied primarily on visual inspection, mechanical measurements, ignition-system testing, exhaust-gas analysis and the experience of service technicians. With the introduction of electronic engine management, diagnostics became increasingly based on measured electrical signals and information available from electronic control units. Modern professional diagnostic equipment combines communication with vehicle control units and direct electrical measurements. Systems such as the Bosch KTS family provide ECU communication together with multimeter and oscilloscope functions, allowing

information supplied by the electronic control unit to be compared with signals measured directly from sensors and actuators.

In parallel, Noise, Vibration and Harshness (NVH) analysis has become an important field in vehicle development, condition monitoring and fault diagnosis. An internal combustion engine produces a complex combination of acoustic and vibration components originating from combustion, gas exchange, mechanical impacts, rotating components and auxiliary systems. Changes in these signals may therefore contain useful information about developing faults. Delvecchio, Bonfiglio and Pompoli [1] reviewed vibro-acoustic condition monitoring techniques for internal combustion engines, while acoustic emissions have also been investigated for combustion, intake and exhaust system diagnosis [2]. Such approaches are attractive for workshop use because microphones are inexpensive, simple to install and non-invasive.

The exhaust signal is particularly interesting because combustion processes in individual cylinders produce a periodic sequence of pressure and acoustic events. A change in the combustion process of one cylinder consequently modifies the corresponding exhaust event. Previous studies have demonstrated that exhaust-related information can be used for cylinder-specific misfire diagnosis. Ceccarani, Rebottini and Bettini [3] investigated misfire monitoring through exhaust-pressure analysis, while Chiatti and Chiavola [4] considered misfire diagnosis in spark-ignition engines. These studies confirm that individual combustion irregularities can be recognised through their influence on exhaust-related signals.

Although vehicle electrification is progressing rapidly, spark-ignition internal combustion engines and bi-fuel gasoline/LPG vehicles remain present on the European market. LPG has a higher octane rating than conventional gasoline and therefore high resistance to knock [5]. However, higher octane rating is not itself the reason for more difficult ignition. Of greater diagnostic importance is that gaseous LPG/air mixtures can require higher ignition

voltage at the spark-plug electrodes than gasoline mixtures. Consequently, weaknesses in the ignition system may first become apparent during LPG operation [6,7]. An ignition coil with reduced available secondary voltage, deteriorated insulation, worn spark-plug electrodes or excessive spark-plug gap may still allow apparently normal operation on gasoline while producing occasional weak or incomplete combustion on LPG. For conventional LPG applications, a moderate reduction of the spark-plug gap is therefore sometimes recommended, depending on the engine and spark-plug specification [6,7].

An additional practical observation motivating this study is that early-stage ignition irregularities may initially appear only under unfavourable thermal conditions. In the investigated cases, the irregularity was especially noticeable during LPG operation at high ambient temperatures and after significant thermal loading of the engine compartment. Such behaviour can indicate a thermally sensitive ignition-system fault, for example degradation of an ignition coil or its insulation, although it should not be interpreted as proof of a particular component failure.

At this stage of fault development, combustion is not necessarily completely absent. Instead, an individual cycle may be weaker, slower or incomplete. The resulting irregularity can be clearly audible at the exhaust outlet while the variation in crankshaft acceleration remains insufficient for the onboard diagnostic system to register a cylinder-specific misfire fault. This creates a diagnostic interval in which an experienced technician can hear that engine operation is irregular, but cannot reliably determine the responsible cylinder from sound alone.

Previous exhaust-based studies support the possibility of identifying combustion irregularities from exhaust signals, but many reported approaches use pressure transducers and dedicated measurement arrangements [3,4]. In contrast, the method proposed here uses an external microphone positioned at the exhaust outlet together with the crankshaft position sensor signal. The microphone provides a simple and non-invasive means of detecting changes in consecutive exhaust events, while the crankshaft position signal provides the angular reference required for cylinder identification. Because the acoustic event is detected after a vehicle-dependent delay, an experimentally determined time correction is introduced by intentionally disabling a known cylinder during calibration. This compensates for differences in exhaust-system length and geometry without requiring a detailed physical model of the exhaust system.

The proposed approach is therefore intended as a practical workshop-oriented extension of previously reported exhaust-based diagnostic methods. Its main advantage is the use of a low-cost microphone and a crankshaft reference signal that can be acquired with equipment already common in professional automotive diagnostics. The objective of this study is to identify the cylinder in which an intermittent combustion irregularity occurs before a cylinder-specific OBD misfire fault is generated. The purpose is not to replace conventional OBD monitoring, but to provide supplementary information in cases where the fault can already be heard at the exhaust outlet but cannot yet be localised using standard diagnostic information.

2. METHODOLOGY

2.1. Diagnostic background and investigated combustion irregularity

Misfire monitoring is an important function of modern onboard diagnostic systems because repeated combustion failures increase exhaust emissions and, in severe cases, can cause overheating and damage to the catalytic converter. One of the most widely applied principles for detecting misfire in spark-ignition engines is based on variations in crankshaft rotational speed [8]. During normal combustion, each cylinder contributes torque to the crankshaft during its power stroke. If combustion is absent or substantially weaker in one cylinder, its torque contribution is reduced and a characteristic change in instantaneous crankshaft angular velocity occurs.

The crankshaft position (CKP) sensor detects the passage of teeth on a reluctor or encoder wheel attached to the crankshaft. The time interval between successive teeth is related to instantaneous rotational velocity, while one or more missing teeth provide an angular reference. By comparing successive tooth intervals, the engine control unit can evaluate abnormal acceleration or deceleration associated with individual combustion events. The exact criterion for setting a diagnostic trouble code and activating the malfunction indicator depends on regulation, manufacturer strategy, operating conditions and fault severity. Consequently, sporadic weak-combustion events can occur before the OBD system identifies and stores a cylinder-specific fault.

Knock sensors should be distinguished from the primary crankshaft-based misfire detection principle. Automotive knock sensors generally contain a piezoelectric sensing element mounted on the engine block. Their main purpose is to detect structure-borne vibration associated with knock so that the engine control unit can modify ignition timing. The condition investigated in this paper lies between normal combustion and complete misfire: combustion is still present, but the corresponding exhaust event differs sufficiently from normal events to produce an audible irregularity. This situation can be particularly useful diagnostically in gasoline/LPG vehicles because gaseous-fuel operation can reveal marginal ignition components before the same symptom becomes apparent on gasoline.

2.2. Measurement setup, calibration and signal processing

The proposed measurement system uses two signals acquired simultaneously with a conventional two-channel digital oscilloscope or an equivalent synchronised acquisition system. The CKP sensor signal is connected to the first channel without interrupting normal engine operation, while a microphone positioned close to the exhaust outlet is connected to the second channel. The purpose of the microphone is not absolute sound-pressure-level measurement but observation of the temporal structure of consecutive exhaust events. Its position is therefore kept fixed during calibration and diagnostic measurements.

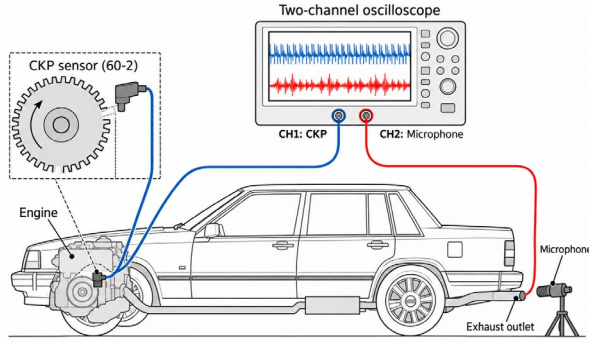


Fig. 1 Experimental setup for simultaneous acquisition of the CKP signal and exhaust acoustic signal using a conventional two-channel oscilloscope

For a four-stroke engine, one complete working cycle corresponds to 720° of crankshaft rotation. The sequence of combustion events within this interval is determined by the firing order. The CKP reluctor pattern provides the crankshaft reference. If the wheel contains N theoretical equally spaced positions, the nominal crank angle represented by one position is $\Delta\varphi = 360^\circ/N$. For a conventional 60-2 wheel, each theoretical tooth position therefore corresponds to 6° of crankshaft rotation.

For approximately constant rotational speed over the short analysis interval, time can be directly related to crankshaft angle. If n denotes engine speed in revolutions per minute and t is time in seconds, the crankshaft angle elapsed during that interval is:

$$\theta(t) = 6nt \quad (1)$$

$$T_{720} = 120/n, \quad T_{360} = 60/n, \quad T_{180} = 30/n \quad (2)$$

where T_{720} , T_{360} and T_{180} are the time durations corresponding to 720° , 360° and 180° of crankshaft rotation, respectively. At 800 rpm these durations are 150 ms, 75 ms and 37.5 ms. At 1000 rpm, a 180° firing interval is 30 ms. Thus, for a four-cylinder four-stroke engine, the diagnostic waveform can be expanded to a time window of approximately 30–40 ms at idle to inspect individual consecutive combustion-related events.

A direct comparison of the CKP and microphone signals is not sufficient for cylinder identification because the acoustic disturbance is detected at the exhaust outlet after an effective delay. This delay includes propagation through the exhaust system as well as contributions from exhaust geometry, gas temperature, catalyst and silencer elements, microphone position, and the measurement channels. Rather than modelling these influences separately, the proposed method determines their combined effect experimentally by calibration.

During calibration, ignition of one known cylinder, preferably cylinder 1, is intentionally disabled for a short period under controlled workshop conditions. The resulting incomplete-combustion or misfire event produces a pronounced modification of the exhaust acoustic waveform. Because the disabled cylinder is known, this event establishes the reference relationship between the CKP pattern and the corresponding acoustic disturbance. The effective delay is defined as:

$$t_d = t_{acoustic} - t_{reference} \quad (3)$$

The equivalent angular displacement associated with any residual timing offset Δt can be expressed as:

$$\Delta\theta = 6n\Delta t \quad (4)$$

where $\Delta\theta$ is expressed in degrees. This relation also shows why calibration is important: even a small timing offset can correspond to a substantial crank-angle error at higher engine speed.

The experimentally determined delay is treated as an effective synchronisation parameter rather than as the theoretical speed-of-sound propagation time through a straight pipe. Consequently, the physical exhaust length does not need to be measured and separate corrections for exhaust-system geometry, temperature, silencers, catalyst location or microphone spacing are not required. Their combined influence is included in the calibration offset as long as the measurement arrangement remains unchanged. After calibration, the engine is returned to normal operation and the time-domain acoustic waveform is inspected in successive firing intervals according to the known firing order.

The important difference from conventional OBD misfire monitoring is that the CKP signal is not primarily used to infer the fault from crankshaft-speed variation. In the proposed procedure it provides the rotational reference and establishes the duration and sequence of firing intervals, whereas the diagnostic information is obtained directly from the time-domain exhaust acoustic waveform. This simplifies practical application because a technician can acquire the CKP and microphone signals on an ordinary two-channel oscilloscope, perform a one-time cylinder-1 calibration, and subsequently compare the acoustic response associated with successive cylinders.

In addition to direct inspection of the raw microphone waveform, the amplitude envelope of the time-domain signal may also be used as a supplementary representation because it can make local changes associated with weak or incomplete combustion easier to recognize. In this study, however, the analysis and figures are based on the original time-domain waveform, while the envelope is mentioned only as a possible aid for future automatic or visual event detection.

3. RESULTS AND DISCUSSION

The experimental evaluation first considered the CKP pattern as a crankshaft reference. The idealised 60-2 waveform shown in Fig. 2 provides a repeatable angular marker every 360° of crankshaft rotation and therefore enables segmentation of the engine cycle. Because the same pattern repeats during both crankshaft revolutions, however, the CKP signal alone does not identify which 360° interval of the 720° four-stroke cycle contains a given acoustic event. Cylinder assignment therefore requires either an additional phase reference or the vehicle-specific calibration described below.

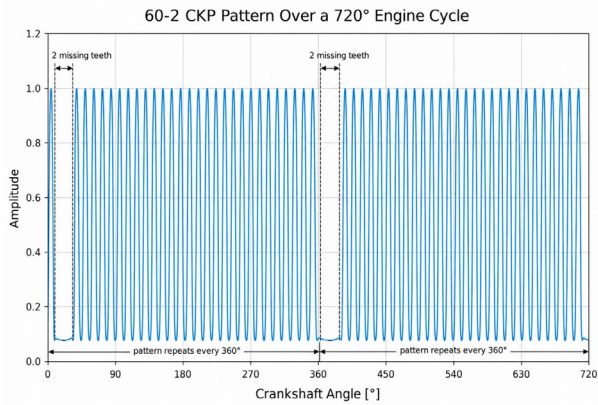


Fig. 2 Idealised 60-2 CKP pattern over a 720° engine cycle. The missing-tooth gap repeats every 360° and provides the crankshaft reference used for cycle segmentation

Figure 2 illustrates the angular information supplied by the CKP signal. For a 60-2 wheel, one theoretical tooth position corresponds to 6° of crankshaft rotation. The missing-tooth region is therefore useful for defining repeatable crankshaft-relative time intervals, while the calibrated acoustic offset is used to establish the correspondence with the firing sequence.

A preliminary software implementation was also used to examine a crank-angle-related time-frequency representation of the microphone signal together with the measured CKP waveform (Figs. 3 and 4). The screenshots demonstrate that the CKP and acoustic information can be displayed together, but they also reveal the practical limitations of this representation for the present diagnostic task. The short-duration combustion-related disturbance is distributed across time and frequency by the finite analysis window, and small synchronisation errors further reduce the clarity of cylinder-specific interpretation.

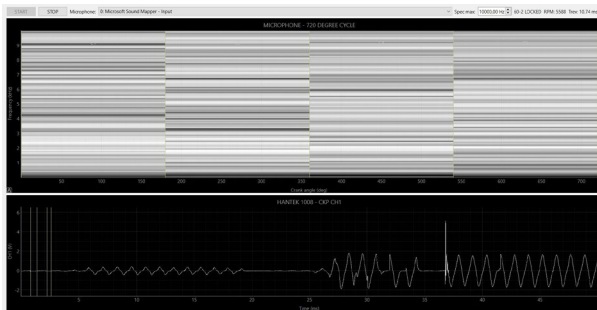


Fig. 3 Preliminary combined display of the microphone time-frequency representation and the measured CKP waveform

In Fig. 3 the time-frequency image provides an overview of the acoustic content, whereas the CKP trace provides the rotational reference. For identifying an individual weak or incomplete combustion event, however, the relevant short transient is not as visually distinct as it is in the original waveform.

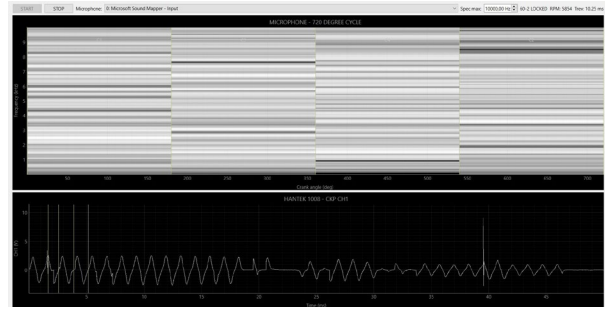


Fig. 4 Second example of the preliminary combined microphone/CKP display, illustrating the limited visual separation of individual combustion-related events in the time-frequency representation

The same limitation is evident in Fig. 4. These observations motivated the use of the time-domain waveform as the primary diagnostic representation. An amplitude envelope may be used as an optional visual aid because it can emphasize local changes in signal magnitude, but it is not required for the basic procedure and is not used as a separate analysis stage in the figures presented here.

The time-domain comparison is shown in Figs. 5 and 6. Figure 5 presents a five-second interval recorded during regular engine operation and during deliberately generated cylinder-1 misfire. Even over this relatively long interval, the misfire condition produces repeated local deviations in waveform amplitude and shape that are visibly different from the more uniform pattern observed with all cylinders operating.

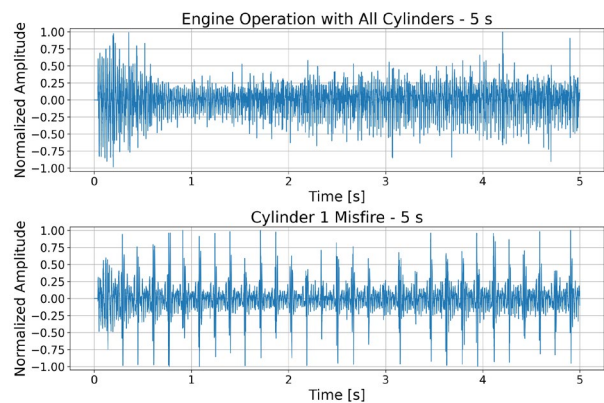


Fig. 5 Exhaust acoustic waveform over a 5 s interval: regular operation with all cylinders (top) and deliberately generated cylinder-1 misfire (bottom)

The deliberately generated cylinder-1 fault therefore provides a clear reference signature for calibration. A naturally developing ignition fault may produce a smaller disturbance because combustion can still occur, although with reduced intensity or altered timing; consequently, the diagnostic criterion is a repeatable deviation in waveform amplitude, shape or local energy rather than complete disappearance of an exhaust pulse.

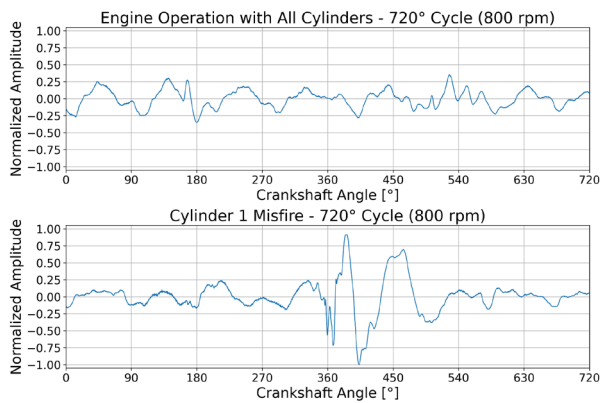


Fig. 6 Exhaust acoustic waveform over one 720° engine cycle: regular operation with all cylinders (top) and deliberately generated cylinder-1 misfire (bottom)

When the same signals are viewed over one 720° cycle (Fig. 6), the difference becomes considerably easier to interpret. The deliberately generated misfire produces a pronounced localised disturbance within the combustion sequence. After cylinder 1 has been used to determine the effective CKP-to-acoustic offset, the remaining firing events can be followed according to the known firing order, with consecutive events separated by 180° of crankshaft rotation in a four-cylinder four-stroke engine.

From a workshop perspective, the procedure can therefore be performed with a conventional two-channel oscilloscope. Channel 1 is connected to the CKP signal and Channel 2 to a microphone positioned close to the exhaust outlet, as shown in Fig. 1. At idle, the time base is expanded to approximately one firing interval, typically about 30–40 ms depending on engine speed. Ignition is then briefly disabled on cylinder 1 to establish the reference acoustic position. After normal ignition is restored, consecutive time-domain events are compared in the known firing order, and the cylinder whose event repeatedly exhibits the abnormal waveform can be selected for conventional ignition, injection or mechanical testing.

The calibration offset is treated as one effective experimental parameter rather than as a theoretical sound-propagation time. It therefore incorporates the combined influence of exhaust-system length and geometry, gas temperature, catalyst and silencers, microphone position and acquisition-channel delay. These quantities do not have to be measured or modelled separately, provided that the measurement arrangement remains unchanged during calibration and diagnosis.

For repeatable use, the calibration record should include engine speed, firing order, CKP reluctor pattern, the cylinder-1 reference offset, microphone position and oscilloscope time-base setting. The principal requirement is not an absolute physical propagation delay, but a stable relative relationship between the deliberately generated reference event and subsequent measurements on the same vehicle.

4. CONCLUSION

A simple time-domain acoustic method for early localisation of intermittent combustion irregularities in individual cylinders has been proposed. It is intended for

diagnostic situations in which an abnormal combustion event is already audible at the exhaust outlet but has not yet developed into a sufficiently pronounced misfire for conventional onboard diagnostics to provide reliable cylinder-specific information.

The experimental observations indicate that the time-domain representation is more suitable for this diagnostic task than the examined time-frequency representation. As demonstrated by the comparison in Figs. 5 and 6, short combustion-related disturbances remain directly visible as changes in waveform amplitude and shape, whereas spectrogram processing can reduce their visual contrast because of the finite analysis window. The amplitude envelope may additionally assist visual or automatic detection of local deviations, but the proposed diagnostic procedure can be performed directly on the measured time-domain waveform.

For a four-stroke engine, the CKP reference permits the oscilloscope time base to be related to crankshaft rotation using $\theta(t) = 6nt$. The corresponding durations are $T_{720} = 120/n$, $T_{360} = 60/n$ and $T_{180} = 30/n$. Thus, at typical idle speeds a single firing interval is of the order of several tens of milliseconds (37.5 ms at 800 rpm and 30 ms at 1000 rpm), which can be readily displayed on a conventional oscilloscope.

Cylinder identification is established by a simple vehicle-specific calibration. Ignition is intentionally disabled on cylinder 1 for a short period and the resulting acoustic disturbance is used to determine the effective offset between the CKP reference and the exhaust waveform. This experimentally determined correction incorporates the combined influence of exhaust-system length and geometry, gas temperature, catalyst and silencers, microphone position and acquisition delay. Consequently, these quantities do not have to be measured or modelled separately, provided that the measurement arrangement remains unchanged.

After calibration, the engine is returned to normal operation and successive time-domain events are followed according to the known firing order. A weak or incomplete combustion event can then be associated with the cylinder whose calibrated waveform interval shows a repeatable deviation. The resulting procedure requires only a two-channel oscilloscope, access to the CKP signal and an exhaust microphone, making it suitable as a low-cost workshop-oriented supplement to conventional OBD diagnostics. Further work should quantify calibration repeatability and diagnostic sensitivity on a larger number of gasoline and gasoline/LPG vehicles and should evaluate automatic time-domain event detection under varying engine speeds and load conditions.

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NOISE FROM GARDEN TOOLS: MEASUREMENT-BASED CHARACTERIZATION, EXPOSURE ASSESSMENT AND IMPLICATIONS FOR LOW-NOISE DESIGN

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Abstract. Garden tools are a widespread but insufficiently quantified source of environmental and occupational noise, particularly in residential environments. Their acoustic impact is often underestimated due to variability in operating conditions and limited comparability of declared emission data. This paper presents a systematic experimental analysis of noise emissions from selected garden tools under realistic operating regimes. A-weighted sound pressure levels (L_{Aeq}) were obtained through in-situ measurements, while sound power levels (L_{WA}) were estimated using standardised engineering approaches, incorporating sound propagation effects such as geometrical divergence and atmospheric attenuation. The results are critically compared with manufacturers' declared values and relevant occupational exposure limits, revealing notable discrepancies under real-use conditions. The analysis includes both broadband levels and indicative spectral characteristics, enabling a more comprehensive assessment of user exposure and environmental impact. A comparative evaluation between petrol-powered and battery-powered devices shows consistently lower emission levels for battery tools, along with more favourable acoustic signatures. These findings are relevant not only for exposure reduction but also for the design and optimisation of low-noise equipment. Furthermore, the study highlights the role of personal protective equipment and discusses the potential of digital and sensor-based measurement systems for continuous noise monitoring and data-driven improvement of acoustic performance. The presented approach contributes to improved measurement practices, more realistic risk assessment, and supports the development of quieter technologies in line with sustainable engineering principles.

Key words: Environmental acoustics, Garden tool noise, Sound power level (L_{WA}), L_{Aeq} , Noise exposure, Measurement methods

1. INTRODUCTION

Noise is one of the most widespread environmental risk factors in both living and occupational environments. Despite the fact that noise is often treated as an inevitable byproduct of human activity, it is increasingly recognized from a sustainable development perspective as a major element of environmental impact that can be managed, measured, and reduced. Garden tools, which include petrol and electric lawnmowers, chainsaws, leaf blowers, scarifiers, and trimmers, represent a specific segment of noise sources because they are operated in close proximity to the user and frequently within residential areas, where

they affect the quality of life for a large number of inhabitants.

Workers operating these tools are undoubtedly exposed to noise. Therefore, it is essential to comply with the regulations set forth in the Rules on the protection of workers from the risks related to exposure to noise at work, which prescribes exposure limit values and measures that the employer is obliged to implement if these limits are exceeded. Furthermore, the data specified by manufacturers in technical data sheets or energy labels must be verified and measured in accordance with the Slovenian standard SIST ISO 9612: Acoustics – Determination of occupational noise exposure: Engineering method.

In the European Union, there is a clearly harmonized framework regarding environmental noise legislation that regulates noise sources at local or national levels. The labelling of garden tools is covered by Directive 2000/14/EC of the European Parliament and of the Council of 8 May 2000 on the approximation of the laws of the Member States relating to the noise emission in the environment by equipment for use outdoors, and must include [1-5]:

- the CE marking, visibly, legibly, and indelibly affixed to each piece of equipment;
- indication of the guaranteed sound power level L_{WA} in dB(A), referenced to 1 pW.

Directive 2000/14/EC was subsequently amended by regulations in 2005, 2009, and 2019, and corrected in 2021. The purpose of this directive is to improve the control of noise emissions for 57 different types of equipment used outdoors to:

- promote the smooth functioning of the EU single market;
- improve the health and well-being of citizens by reducing noise emitted by equipment used outdoors.

The green transition requires a fundamental transformation of technologies and practices that lower noise emissions, promote digital monitoring of environmental parameters, and enable the development of quieter and more environmentally friendly devices. The analysis of noise from garden tools thus sits at the intersection of technical, health, environmental, and social aspects of sustainable development. Crucial elements here

include understanding the physical mechanisms of sound propagation, objective comparison of declared and measured levels, user risk assessment, and the broader social context of understanding noise as an environmental pressure.

This paper is based on field measurements of sound pressure levels of selected garden tools, the calculation of emission sound power levels based on geometric divergence and atmospheric absorption, and a comparison of the results with regulatory exposure limits. In addition to the technical results, the article addresses the importance of noise in shaping sustainable practices, the impact on user health and well-being, and the opportunities for transitioning to quieter technologies.



Fig. 1 Noise measurement of garden tools. Left: field measurements. Right: garden tools used in the study (Source: Alen Lamper, 01/04/2025)

2. METHODS AND THEORETICAL BACKGROUND

2.1. Measurement of Sound Pressure Levels

The user's exposure was assessed through measurements of the sound pressure level L_{pA} at a distance of 1–1.5 m from the source, complying with the guidelines of the SIST ISO 9612 standard for workplace noise assessment [6-10]. Measurements were carried out during the regular operation of the devices in a natural environment [11].

2.2. Calculation of Emission Sound Power Level

Since laboratory measurements according to SIST ISO 3744 could not be performed, the emission sound power level L_{WA} was calculated from the measured sound pressure level using spherical divergence:

$$L_w = L_p - 10 \log K + 20 \log r + 11, \quad (1)$$

where L_w is the radiated sound power level of the source, and L_p is the sound pressure level measured at a distance of r metres from the source. The term $10 \log K = 0.13$ dB depends on atmospheric conditions. Attenuation due to atmospheric absorption was also accounted for using the following term:

$$A_{\text{atm}} = \alpha \cdot r \quad (2)$$

The atmospheric attenuation coefficient α was applied according to the specific frequency range (ISO 9613-2).

2.3. Comparison with Legislation and Exposure Limits

The Rules on the protection of workers from the risks related to exposure to noise at work (Official Gazette of the RS, Nos. 17/2006, 18/2006 – cor.) and Directive 2003/10/EC in the EU define exposure limit values and exposure action values (Table 1) [12,13].

Table 1 Main noise exposure limit values

Exposure Limit	Avg. Level, dB(A)	Peak, dB(C)
Lower action value	80 dB	135 dB
Upper action value	85 dB	137 dB
Limit value	87 dB	140 dB

2.4. Subjective and Psychoacoustic Analysis

In the present study, the psychoacoustic aspects are considered as an interpretive framework; formal psychoacoustic metrics such as sharpness and tonality were not independently quantified.

Evaluations and sound power levels are repeatable and accurate. However, when seeking ways to intuitively understand how much louder one device actually is compared to another, the logarithmic scale can present a hurdle. For instance, if a petrol lawnmower has a sound power level of 100 dB(A), what would be the sound power level of a lawnmower that is 10 percent quieter or 10 percent louder? (90 dB(A) or 110 dB(A) is, of course, incorrect). Every comparison, whether computational or subjective, carries significant margins of error, especially if the sound spectrum is non-uniform, contains relatively large tonal components, or varies over time. It is well known that broadband noise has a different subjective loudness than a pure tone at the same level.

Psychoacoustics is the scientific discipline that studies how humans perceive and interpret sounds. It bridges the physical properties of sound (such as frequency, loudness, and spectrum) and human subjective sound perception. Because the perception of the same acoustic event is not identical or uniform across all subjects, psychoacoustics introduced criteria for acoustic events known as sound quality. Regarding how psychoacoustics links to garden tool noise, a simple example can be given: psychoacoustic measurements can help improve tool design to make them less burdensome for the operator. Although two lawnmowers might have the exact same L_{WA} in dB(A), one may feel more annoying due to higher pitches or vibrations. Electric tools are often less disruptive because they generate fewer low-frequency components and vibrations than petrol-powered ones. When assessing the impact of noise, its subjective perception was taken into account, focusing particularly on: tonality, sharpness, temporal fluctuations, spectral characteristics of battery vs. petrol engines. These parameters significantly affect perceived annoyance and well-being, which is directly relevant to social and health impacts [14-17].

3. MEASUREMENT RESULTS AND DISCUSSION

For the measurements, we utilised an NTi XL2 sound level meter borrowed from the laboratory of the Faculty of Environmental Protection. It is a versatile, high-precision sound level meter designed for professional use in environmental noise monitoring, building acoustics, and occupational noise assessment. It is certified as a Class 1 sound level meter, fulfilling standards such as IEC 61672-1 [18]. It displays all results simultaneously and includes a function to save data to a removable SD card for subsequent documentation. Additionally, audio recordings can be appended to each individual measurement.

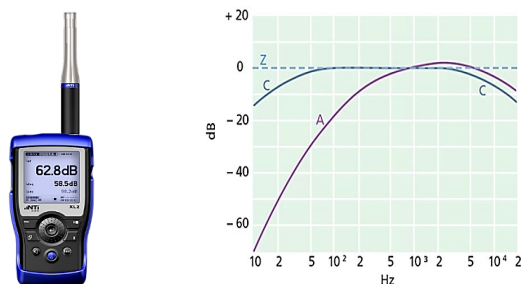


Fig. 2 NTi Audio XL2-TA Sound Meter. On the right are the frequency-weighting characteristics (NTi Audio, n.d.)

Frequency weighting A: the A-weighting curve describes the sensitivity of the human ear at lower sound levels (40 dB(A)). The range of maximum audibility is between 1000 and 4000 Hz. Sound attenuates at higher and lower frequencies. Frequency weighting C: The response of the human ear to noise varies depending on the noise level. Frequency weighting C is used in the range above 100 dB. It is particularly useful for estimating maximum sound pressure levels and measuring impulse noise. Frequency weighting Z: Zero frequency weighting refers to a frequency response between 10 Hz and 20 kHz without frequency correction.

3.1. Comparison of Measured and Declared Values

Table 2 (below) summarises the results of six months of measurements taken during the operation of 18 different tools.

Data analysis from the measurements reveals that for most tools, the measured values deviate from those declared. For certain devices (e.g., Makita DUC306, Makita DUX60 brushcutter, Stihl FS460C), the measured values are substantially higher than declared, indicating a potential underestimation of the user's actual sound exposure. For other units (e.g., Stihl MS271, Stihl MS500i), the declared figures match the measurements more closely. The results indicate that declared values may not always represent the sound levels encountered under real operating conditions.

A comparison between the declared sound power and the sound power calculated from field measurements shows a very similar trend. For several tools (e.g., Makita DUC306, Stihl MS500i, Husqvarna S500), the calculated values exceed the declared ones, indicating a higher noise impact on the surrounding environment than stated by the manufacturer. A few examples (e.g., Stihl MS271, Stihl

MS180) show relatively good alignment. Nevertheless, the overall tendency is that declared values, on average, underestimate actual outcomes, which has critical implications for risk assessment regarding both the user and the environment.

Table 2 Summary of measured, declared, and calculated noise values

Tool Model	Meas. L_{Cpeak} [dB]	Meas. L_{Aeq} [dB]	Decl. L_{WA} [dB]	Decl. L_{pA} [dB]	Calc. L_W [dB]
Makita DUB362	96.7	84.3	93.5	79.1	95
Makita DUC306	114.0	97.6	103.0	89.0	108
Makita DUC254	108.0	93.0	103.0	92.0	105
Makita DUX60 trim.	95.4	85.8	88.0	74.0	97
Makita DUX60 brush.	112.2	95.2	88.0	74.0	106
Stihl FS460C	112.4	97.4	113.0	101.0	108
Stihl HS82R	103.6	95.1	107.0	94.0	106
Stihl BG36	110.7	98.3	104.0	90.0	109
Stihl MS180	118.8	102.2	112.0	100.0	113
Stihl MS271	116.4	104.8	116.0	105.0	116
Stihl MS500i	130.6	114.7	119.0	106.0	126
Weibang WB537	106.1	88.8	98.1	86.8	100
Ramda mower	104.3	87.4	102.0	85.0	98
Ramda scarif.	106.0	88.7	104.0	85.0	100
Husqvarna S500	107.2	91.7	98.0	83.3	103
Struc Muta	104.5	89.1	96.0	85.0	100
Drilling machine	110.0	97.5	105.0	91.0	108
Karcher HDS8	100.7	89.8	93.0	74.0	100

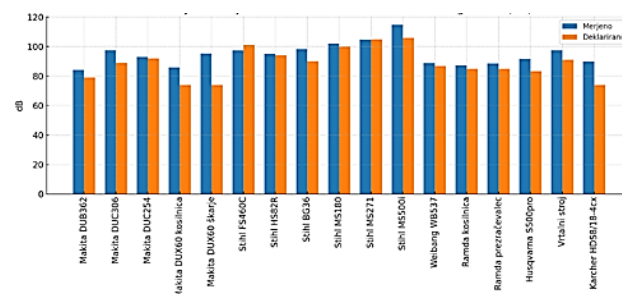


Fig. 3 Comparison of measured and declared sound pressure values

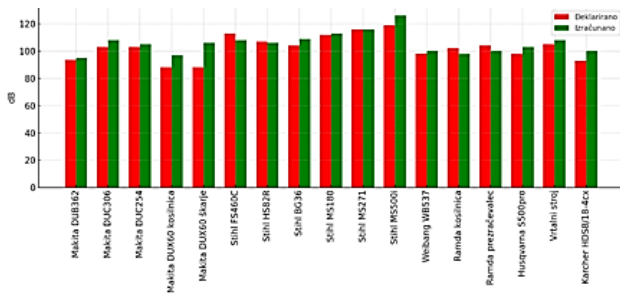


Fig. 4 Comparison between declared and calculated sound power levels

The comprehensive analysis of all measured garden tools demonstrated: discrepancies between declared and measured sound power levels were present across the majority of devices; for certain petrol-powered tools, measured levels exceeded declared levels by up to 5–8 dB; battery-powered tools, on average, exhibited noise levels 10–1 dB lower than comparable petrol-powered units. These differences are consistent with the different operating principles of the two technologies; petrol engines may produce more pronounced mechanical and low-frequency components, whereas battery-operated motors generally exhibit different spectral characteristics.

3.1.1 Statistical Analysis of Declared and Measured Noise Levels

To strengthen the comparison between manufacturer-declared values and field measurements, a statistical assessment of the observed deviations was performed. The analysis focused on the difference:

$$\Delta L = L_{\text{measured}} - L_{\text{declared}} \quad (3)$$

for both sound pressure levels and calculated sound power levels.

Across the investigated devices, positive deviations predominated, indicating that real operating conditions frequently resulted in higher acoustic emissions than those suggested by product specifications. The observed differences ranged from negligible values (< 1 dB) to deviations exceeding 8 dB for several petrol-powered devices.

From an acoustical perspective, a difference of 3 dB represents approximately a doubling of acoustic energy, while differences of 5 to 10 dB may be clearly perceptible to human listeners. Consequently, even moderate discrepancies between declared and measured values may substantially affect occupational exposure assessment and the selection of hearing protection strategies.

The results suggest that laboratory-based declaration procedures provide useful comparative information but may underestimate real-world exposure conditions where load variations, operator behaviour, vegetation density and environmental reflections affect emitted noise levels.

3.1.2 Exposure Duration Analysis and Daily Noise Dose

Noise-related health risks depend not only on sound level but also on exposure duration. Therefore, the

measured values may be interpreted using the equal-energy principle that underlies occupational noise regulations.

The permissible exposure duration can be estimated according to:

$$T = 8 \cdot 2^{\frac{85 - L_{\text{Aeq}}}{3}}, \quad (4)$$

where: T is allowable exposure time (h); L_{Aeq} is measured A-weighted equivalent sound level (dB(A)).

Application of this relationship indicates that relatively small increases in noise level lead to substantial reductions in permissible exposure duration. Examples are presented in Table 3.

Table 3 Estimated allowable exposure durations at selected A-weighted equivalent sound pressure levels

L_{Aeq} , dB(A)	Allowable Exposure
85	8 h
88	4 h
91	2 h
94	1 h
97	30 min.
100	15 min.

Several petrol-powered chainsaws, brush cutters and leaf blowers investigated in this study exceeded 95 dB(A), implying that prolonged operation without hearing protection may rapidly result in excessive daily noise doses. In contrast, most battery-powered tools remained within a range that permits significantly longer operating periods before equivalent daily exposure limits are reached.

These findings demonstrate that exposure duration should be considered together with instantaneous noise level when selecting equipment and planning maintenance activities.

3.2. Estimated Operator Exposure

In more than 70 % of cases involving petrol-powered tools, the upper exposure action value of 85 dB(A) was exceeded, and for chainsaws and leaf blowers, the level frequently crossed the 87 dB(A) threshold. Conversely, battery-powered tools generally remained below 85 dB(A), with certain lawnmowers even dropping below 80 dB(A). This translates into significantly lower health and safety risks, the possibility of operating without mandatory additional personal protective equipment (PPE), and enhanced subjective comfort during operation.

3.3. Sustainability Effects and Environmental Aspects

Noise plays a fundamental role in sustainable environmental management because it impacts human health directly, degrades the quality of life in urban residential areas, increases stress and induces sleep disturbances, and disrupts wildlife and ecosystems (e.g., birds, pollinators). Transitioning to battery-powered equipment simultaneously yields lower noise emissions, decreased CO₂ emissions, reduced local air pollution, and attenuated mechanical vibrations (reducing the risk of HAVS – hand-arm vibration syndrome) [19-24].

3.4. Social Aspects and Regulation

In recent years, debates across Europe have intensified regarding restricting petrol-powered garden tools in urban zones, introducing specific time slots and operating limits for noisy equipment, deploying smart measurement networks to monitor urban noise, and raising user awareness concerning personal acoustic protection. In Slovenia, the key challenges remain low public awareness and a total lack of enforcement or oversight in private, non-commercial tool use.

3.5. Measurement Uncertainty and Limitations

The field measurements presented in this study provide a realistic indication of the acoustic conditions encountered during the operation of garden tools. However, several methodological limitations should be considered when interpreting the results. Unlike standardised laboratory measurements, field measurements are influenced by the operating regime of the machine, distance and position of the measurement microphone, ground and surrounding surfaces, atmospheric conditions, and temporal variations in the emitted noise.

Measurements were performed using an NTi XL2 Class 1 sound level meter, providing an appropriate level of accuracy for environmental and occupational noise assessment. The measurements were conducted at a distance of approximately 1 – 1.5 m from the operating source under normal working conditions. Because the measurements were performed in a natural environment rather than in an acoustically controlled test facility, the measured L_{Aeq} values should be regarded as representative of the investigated operating conditions rather than as standardised product emission values.

A further limitation concerns the estimation of the A-weighted sound power level (L_{WA}). Since standardised laboratory measurements according to ISO 3744 were not available, the sound power level was estimated from the measured sound pressure level by considering geometrical divergence and atmospheric absorption. This approach provides a useful engineering estimate, but it does not replace a standardised determination of sound power in a controlled acoustic environment. Consequently, differences between calculated and manufacturer-declared L_{WA} values should be interpreted primarily as an indication of potential differences between laboratory declaration conditions and real-use conditions, rather than as direct evidence of non-compliance by manufacturers.

The comparison of declared and measured values nevertheless indicates that manufacturer specifications do not necessarily describe the acoustic exposure experienced by the operator during actual use. For several investigated tools, measured levels were higher than the corresponding declared values. This finding emphasizes the importance of distinguishing between product emission data, which are normally obtained under prescribed test conditions, and occupational exposure, which depends on the actual operating time, working position, distance from the source and operating regime.

The exposure assessment should also distinguish between instantaneous or short-term measured sound levels and the daily noise exposure level. The exposure action values of 80 and 85 dB(A), and the exposure limit

value of 87 dB(A), are related to occupational exposure and should therefore be interpreted in the context of the normalised daily exposure level and exposure duration. A measured L_{Aeq} above one of these values does not by itself establish that the corresponding daily exposure limit has been exceeded. The results presented here should therefore be understood as an indication of potential exposure and as a basis for identifying tools and operating conditions requiring additional assessment and protective measures.

Another limitation is the relatively limited number of investigated devices and models. The study included 18 garden tools and therefore cannot be considered representative of all commercially available petrol- and battery-powered equipment. Nevertheless, the measurements cover several common categories of garden machinery and provide a useful basis for identifying general tendencies. Further research should include a larger number of models, repeated measurements under controlled operating conditions, and standardised sound-power measurements.

In addition to A-weighted sound levels, future investigations should place greater emphasis on the spectral characteristics of garden-tool noise. Frequency spectra, tonality, low-frequency components, temporal variability and psychoacoustic parameters could provide additional information about perceived annoyance and acoustic comfort. Such measurements would be particularly valuable when comparing tools with similar L_{Aeq} or L_{WA} values but different acoustic signatures.

Overall, the present study demonstrates the value of combining standardised acoustic concepts with measurements obtained under realistic operating conditions. The results should not be interpreted as a replacement for standardised product certification measurements, but rather as complementary information for occupational risk assessment, environmental noise evaluation and the development of quieter garden equipment.

3.6. Extended Psychoacoustic Metrics and Spectral Annoyance Analysis

The results of the L_{Aeq} or L_{WA} measurements confirm that broadband values in dB(A) fail to capture the full complexity of human noise perception regarding garden tools. Although battery-powered equipment exhibits, on average, 10 – 15 dB lower noise levels than petrol alternatives, frequency analysis reveals significant variations in their spectral composition. Petrol engines generate pronounced low-frequency components and mechanical vibrations. Due to their long wavelengths, these components propagate more easily through obstacles, inducing higher roughness and temporal fluctuations.

Conversely, battery-powered tools shift acoustic energy into higher frequency bands, primarily driven by high electromotor rotational speeds and aerodynamic blade noise. This phenomenon substantially elevates the sharpness metric, which the human ear subconsciously perceives as more annoying or piercing, despite a lower overall acoustic energy level. Consequently, the application of standard A-frequency weighting frequently

underestimates the actual level of annoyance associated with electric motors.

To achieve a more precise exposure assessment, it is essential for future research to implement advanced psychoacoustic parameters in accordance with the ISO 532-1 (loudness) standard. This approach will allow for an objective evaluation of the interaction between the physical sound field and the operator's neurological response, thereby facilitating the development of equipment with a more favourable acoustic signature.

3.7. Engineering Guidelines for Optimisation and Low-Noise Design

Bridging the gap between manufacturers' declared specifications and real-world exposure levels demands a transition toward systemic low-noise design principles [25-31]. Based on the experimental analyses conducted and the identified discrepancies, three primary engineering directions for optimising garden equipment can be established:

- **Aerodynamic Optimisation of Rotating Elements:** For lawnmowers and leaf blowers, the majority of aerodynamic noise stems from turbulence at the blade edges or impeller blades. Implementing bionic profiles (e.g., serrated trailing edges inspired by owl wings) can mitigate vortex shedding. This reduces noise levels within the critical frequency range of 1000 Hz to 4000 Hz, where the human ear exhibits peak sensitivity.
- **Structural Damping and Acoustic Enclosures:** For petrol-powered machinery, utilising advanced polymer composites with a high internal friction damping factor is imperative. This prevents structural sound from transmitting from the engine to the outer housing panels, which otherwise act as secondary noise radiators. Integrating micro-perforated panels within engine shrouds provides efficient absorption without compromising cooling efficiency.
- **Vibration Isolation at Interface Surfaces:** Reducing the incidence of Hand-Arm Vibration Syndrome (HAVS) requires complete acoustic and mechanical decoupling of handles from the primary vibration source via elastomeric isolators. Optimising these elements simultaneously lowers secondary noise generated by loose fittings or joints during high-load operations.

By combining these measures, manufacturers can achieve real noise reduction at the source, which mitigates long-term environmental noise pressures and decreases reliance on personal protective equipment (PPE).

4. NOISE AND THE GREEN TRANSITION: OPPORTUNITIES AND CHALLENGES

The green transition encompasses technological, social, and political transformations. The findings of this study show that: **Technological Opportunity:** Battery-operated tools enable a massive reduction in noise emissions while simultaneously being more energy-efficient and ecologically benign. **Digitalisation:** The deployment of

mobile measurement systems, networked sensor arrays, and artificial intelligence is critical for tracking urban noise, managing environmental metrics, and formulating adaptive local policies. **Social Impact:** Mitigating noise exposure improves public health, lowers community stress levels, and elevates general urban livability. **Regulatory Framework:** Although Directive 2000/14/EC strictly dictates the labelling of sound power, practical measurements reveal persistent deviations, which underscores the urgent need for independent verification frameworks.

5. CONCLUSION

The following definitive conclusions can be drawn:

1. Noise exposure during garden tool operation frequently exceeds legally permitted thresholds. For most petrol tools, measured noise levels were above the action limit (85 dB(A)) and often neared or exceeded absolute limit values (87 dB(A)), indicating that additional protective measures may be required depending on the duration and conditions of exposure.
2. Battery-powered tools were generally quieter than the investigated petrol alternatives, although some measured levels remained above the lower exposure action value of 80 dB(A). The magnitude of the difference should be interpreted in relation to the individual operating conditions and exposure duration.
3. Manufacturers' declared values do not always match real-world measurements. In specific devices, the discrepancies between declared and measured sound power levels exceeded 3 dB, pointing to a clear need for more rigorous verification and market surveillance.
4. Technical, organisational, and personal protective measures remain essential to minimise risk. Selecting quieter (battery) tools, minimising exposure duration, and utilising dual hearing protection (earplugs combined with earmuffs) are highly recommended for the loudest categories, such as leaf blowers and chainsaws.

Noise generated by garden equipment remains a major technical and environmental challenge affecting operator health and neighbourhood quality of life. Field measurements confirm that while petrol devices often border or violate occupational safety boundaries, battery-powered alternatives emerge as a quieter, energy-efficient, and sustainable path forward. From a long-term sustainability perspective, it is imperative to accelerate the shift toward quieter technologies, modernise noise monitoring infrastructure, and enhance end-user safety education. Noise is thus part of the broader interdisciplinary debate on the green transition, demanding integrated technical, ecological, and social approaches.

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ENSURING ACOUSTIC COMFORT IN A CLOSED SPACE FOR HUMAN WELL-BEING

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Abstract. *Inside buildings, technical devices and installations operate, generating noise and vibrations that are very harmful to human life and health. To ensure a comfortable living environment for humans inside buildings, it is necessary to identify the sources of noise and vibrations, determine the propagation mode of these noxious phenomena, measure the characteristic levels, and compare them with the admissible values. To this end, the characteristic parameters of the noise generated by equipment and installations operating within buildings were experimentally determined, and the degree of harmfulness was established by comparing these values with permissible limits. Following these activities, the impact on the interior spaces of buildings was assessed. Based on the results obtained, the necessary measures to ensure acoustic comfort in enclosed residential spaces, as well as their effectiveness, were determined. The paper presents in detail the results of the research undertaken by the authors in this field.*

Key words: *Noise level, Acoustic comfort, Sources of noise, Enclosed spaces*

1. INTRODUCTION

The various technical devices and installations operating within residential buildings constitute significant sources of noise and vibration that negatively affect the lives and activities of the residents.

With the aim of mitigating the negative impact of these harmful factors and ensuring acoustic comfort within the enclosed spaces of residential buildings, we have focused on identifying sources of noise and vibration, highlighting their particularly detrimental effects on human health.

To assess the effects of noise and vibrations in enclosed building spaces and the complexity of the generated acoustic field, characteristic noise parameters were determined through experimental measurements and compared against permissible values. Based on this comparison, the degree of harmfulness of the noise generated by appliances and installations operating within residential buildings was determined. To determine the extent of this harmful impact and ensure acoustic comfort within the enclosed spaces of residential buildings, methods for noise reduction, along with their respective levels of effectiveness, have been established.

2. SOURCES OF NOISE AND VIBRATION WITHIN AN ENCLOSED SPACE

Based on the investigations conducted, it was determined that the sources of noise and vibration within residential buildings include radio receivers, televisions, musical instruments, tenant conversations, walking on floors and stairs, and the slamming of doors, in addition to internal systems such as heating, ventilation, vacuum cleaners, elevators, and electrical transformers. Added to these are household appliances: vacuum cleaners, sewing machines, and washing machines.

At the same time, noise in enclosed spaces can also originate from outside, in the form of shouting, road traffic noise, or industrial noise.

The noise generated by these sources is characterised by specific spectra and levels. In enclosed building spaces, sound waves generated by the mentioned sources undergo reflections off the bounding surfaces, and the resulting reflected waves overlap with the direct waves, contributing to the complexity of the acoustic field.

Noise and vibrations generated by building systems and appliances have detrimental effects on the lives and activities of residents; for instance, a noise level of 65 dB during the day disturbs 45 % of the residents [4].

Noise affects the human nervous system, causing psychophysiological changes and disturbances in blood circulation and sleep; it negatively impacts visual function and the endocrine glands, leading to biochemical imbalances.

To mitigate the effects of noise and ensure normal living and resting conditions for residents, permissible noise level limits have been established for civil and socio-cultural buildings.

In this regard, in accordance with SR 6156:2020 concerning noise protection in civil and socio-cultural buildings, specifically regarding permissible limits and acoustic insulation parameters for living rooms and apartments, the permissible limit for the indoor equivalent noise level caused by external noise sources during the day is 35 dB, with a noise curve of Cz30.

A room can be considered quiet when the sound pressure level of the disturbing noise falls between the Cz30 and Cz40 noise curves [6]. In this case, normal

speech becomes intelligible at relatively long distances, and the phone can be used effectively.

During the night, between 23:00 and 07:00, the continuous equivalent noise level must be reduced by 10 dB compared to daytime values, in accordance with Normative 119 from 2014 issued by the Ministry of Health.

3. THEORETICAL CONSIDERATIONS

In an enclosed space bounded in all directions, sound waves reflecting off the boundary surfaces produce reflected waves that superimpose upon the direct sound waves. In this way, a standing wave regime exists within the enclosed space.

The acoustic field within an enclosed space can be studied using the three-dimensional acoustic wave equation expressed in Cartesian coordinates [1,2]

$$\frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial y^2} + \frac{\partial^2 \phi}{\partial z^2} = \frac{1}{c^2} \frac{\partial^2 \phi}{\partial t^2} \quad (1)$$

where $\phi = \phi(x, y, z, t)$ is the velocity potential at a point with coordinates (x, y, z) inside the enclosed space at a given time t .

Equation (1) can be integrated using the method of separation of variables. To this end, consider

$$\phi = X(x)Y(y)Z(z)e^{i\omega t} \quad (2)$$

The solution to the equation is obtained in the form

$$\phi = C \cos(vx + \varphi_x) \cos(\sqrt{\mu - v^2}y + \varphi_y) \cos\left(\sqrt{\frac{\omega^2}{c^2} - \mu}z + \varphi_z\right) e^{i\omega t} \quad (3)$$

where φ_x , φ_y , and φ_z are constants of integration that can be determined from the initial conditions.

Using the relations

$$p = -\rho_0 \frac{\partial \phi}{\partial t}, v_x = \frac{\partial \phi}{\partial x}, v_y = \frac{\partial \phi}{\partial y}, v_z = \frac{\partial \phi}{\partial z} \quad (4)$$

the acoustic pressure and particle velocity components can be determined, where ρ_0 is the density of the medium in the absence of dissipative forces. For the closed parallelepiped-shaped space under investigation, with side lengths l_x , l_y , and l_z , one obtains $\varphi_x = 0$, $\varphi_y = 0$, $\varphi_z = 0$, and

$$v = \frac{n_x \pi}{l_x}, \mu = \pi \left[\left(\frac{n_z \pi}{l_z} \right)^2 + \left(\frac{n_y \pi}{l_y} \right)^2 \right], \quad \omega = \pi c \sqrt{\left(\frac{n_x}{l_x} \right)^2 + \left(\frac{n_y}{l_y} \right)^2 + \left(\frac{n_z}{l_z} \right)^2} \quad (5)$$

where n_x , n_y , and n_z are zero or integers.

The enclosed space has certain modes of vibration characterised by their natural frequencies, which can be determined using the relationship

$$f = \frac{\omega}{2\pi} = \frac{c}{2} \sqrt{\left(\frac{n_x}{l_x} \right)^2 + \left(\frac{n_y}{l_y} \right)^2 + \left(\frac{n_z}{l_z} \right)^2} \quad (6)$$

by assigning various integer values or zero to n_x , n_y , and n_z .

Given the multitude of values these variables can take, it follows that an enclosed space possesses an infinite number of vibration modes. The frequencies of these modes depend on the shape and dimensions of the space.

The existence of these natural frequencies indicates that an enclosed space behaves like a vibrating system that resonates at specific frequencies – its natural frequencies.

By substituting the values of the integration constants into expression (3), the acoustic pressure at a point in the acoustic field within the enclosed space can be determined from relation (4)

$$p = P \cos(k_x x) \cos(k_y y) \cos(k_z z) e^{i\omega t} \quad (7)$$

where the following notation is used

$$k_x = \frac{n_x \pi}{l_x}, k_y = \frac{n_y \pi}{l_y}, k_z = \frac{n_z \pi}{l_z} \quad (8)$$

Relation (6) allows the frequency of each vibration mode to be considered as a vector in frequency space

$$\bar{f} = n_x \frac{c}{2l_x} \bar{i} + n_y \frac{c}{2l_y} \bar{j} + n_z \frac{c}{2l_z} \bar{k} \quad (9)$$

From expression (9), it can be seen that each normal mode of vibration can be represented by a point in frequency space, with coordinates that are multiples of the length units $c/2l_x$, $c/2l_y$, $c/2l_z$.

In this case, the magnitude of the vector extending from the origin of the coordinate axes to the point in question represents, to scale, the frequency of the corresponding vibration mode. This allows for the calculation of the number and type of vibration modes with natural frequencies falling within a specific frequency range

Specifically, the exact number of normal vibration modes with frequencies below a given frequency f is given by the relation

$$N = \frac{4\pi V}{3c^3} f^3 + \frac{\pi S}{4c^2} f^2 + \frac{L}{8c} f \quad (10)$$

where V is the volume of the enclosed space, S is its total surface area, and L is the perimeter.

To determine the total number of normal vibration modes within a specific frequency band extending from f to $f + df$, when the enclosed space is excited by an arbitrary sound, the expression is differentiated with respect to f , yielding

$$dN = \left(\frac{4\pi V}{c^3} f^2 + \frac{\pi S}{4c^2} f + \frac{L}{8c} \right) df \quad (11)$$

If the bandwidth is comparable to the frequency magnitude, the number of vibration modes existing in that frequency band is determined by calculating the difference between the total numbers of vibration modes with frequencies below $f + df$, both calculated using relation (10).

The natural frequencies of enclosed spaces can be determined experimentally by recording acoustic pressure variations at a point within the enclosure while slowly varying the frequency. To this end, the enclosed space is excited by a sound emitted from a loudspeaker driven by a tone generator.

In the case of real enclosed spaces where boundary surfaces are not perfectly reflective, meaning that acoustic waves undergo a certain dissipation of energy upon impact, the axial, tangential, and oblique standing waves formed within the space will be damped.

The damping term $e^{-\delta t}$ can be introduced into the standing wave equation (7) established earlier by replacing the wave number k with a propagation constant.

The phase angles φ_x , φ_y , and φ_z must also be included in the wave equation, as they are non-zero since the bounding surfaces of the enclosed space are neither rigid nor perfectly reflective.

In this way, taking acoustic pressure as the parameter, the equation for damped standing waves is

$$p = P \cos \left[\left(k_x + i \frac{\delta x}{c} \right) x + \varphi_x \right] \cos \left[\left(k_y + i \frac{\delta y}{c} \right) y + \varphi_y \right] \cos \left[\left(k_z + i \frac{\delta z}{c} \right) z + \varphi_z \right] e^{(i\omega - \delta)t} \quad (12)$$

or, taking into account that

$$k_x = \frac{\omega_x}{c}, k_y = \frac{\omega_y}{c}, k_z = \frac{\omega_z}{c}, \cos i\alpha = \cosh \alpha \quad (13)$$

Equation (12) becomes

$$p = P \cosh \left[(\delta_x - i\omega_x) \frac{x}{c} + \varphi_x \right] \cosh \left[(\delta_y - i\omega_y) \frac{y}{c} + \varphi_y \right] \cosh \left[(\delta_z - i\omega_z) \frac{z}{c} + \varphi_z \right] e^{(i\omega - \delta)t} \quad (14)$$

The phase constants φ_x , φ_y , and φ_z are determined by the boundary conditions at $x = 0$, $y = 0$, and $z = 0$, which must be satisfied.

Studying the acoustic field in a real enclosed space where waves are damped requires knowledge not only of the phase constants, which can be determined as previously mentioned, but also of the attenuation constants. These depend on the acoustic absorption of the boundary surfaces, indirectly through the specific acoustic impedance.

Addressing the problem in its entirety is quite difficult. However, the problem is simpler when only the propagation of axial waves along the Ox axis is considered, with the boundary surfaces normal to this axis being acoustically absorbent, while the other boundary surfaces are perfectly rigid and reflective.

In this case, $\delta = \delta_x$ since $\delta_y = \delta_z = 0$ and $\varphi_y = \varphi_z = 0$, and the expression for acoustic pressure becomes

$$p = P \cosh \left[(\delta_x - i\omega_x) \frac{x}{c} + \varphi_x \right] e^{(i\omega - \delta)t} \quad (15)$$

The initial conditions are used to determine the parameters φ_x , δ , and ω .

Between adjacent enclosed spaces, sound propagates through partition walls and floor slabs. Existing calculation formulae for the attenuation provided by an infinitely extended screen, considering either direct transmission or a screen vibrating like a rigid piston [2], yield values that differ significantly from those obtained experimentally.

To evaluate the attenuation in this case, the following approximate calculation formulae can be used within the frequency range considered

$$\Delta L = 13.5 \lg G + 13 \quad \text{for } G < 100 \frac{\text{kg}}{\text{m}^2},$$

$$\Delta L = 18 \lg G + 8 \quad \text{for } G > 100 \frac{\text{kg}}{\text{m}^2} \quad (16)$$

where G is the mass per unit area of the partition element.

Research on thin partition screens has highlighted that the sound attenuation they provide depends on the screen's structure, reaching maximum values at specific frequencies.

In this regard, the coincidence theory was developed, according to which sound transmission through a partition occurs due to the fact that it undergoes bending vibrations.

In this case, sound transmission increases when the speed of sound coincides with the propagation speed of the bending waves corresponding to a specific frequency of the barrier, known as the critical frequency or limiting frequency. This frequency is given by

$$f_{lim} = \frac{c^2}{2\pi\delta_x^2\theta} \sqrt{\frac{m(1-\sigma^2)}{EI}} \quad (17)$$

For a homogeneous screen, at a sound incidence angle of $\theta = 90^\circ$ and with a mass per unit area of $m = \rho d$, Eq. (17) becomes

$$f_{lim} = \frac{c^2}{2\pi d} \sqrt{\frac{12\rho(1-\sigma^2)}{E}} \quad (18)$$

In these expressions, c represents the speed of sound, E is the elasticity modulus of the screen, I is the moment of inertia per unit width, σ is the Poisson's ratio, and ρ is the density of the material from which the wall of thickness d is made.

Since transmission through the screen reaches a maximum when the sound frequency coincides with the limiting frequency, the aim is to construct the screen so that the limiting frequency lies as close as possible to the edge of the audible frequency range.

4. EXPERIMENTAL DETERMINATIONS

Given the diversity and specific nature of noise and vibration sources in enclosed spaces, only some of them are considered below.

The acoustic field created in enclosed spaces by noise from existing sources is particularly complex. For this reason, it is necessary to investigate it experimentally.

To this end, the noise levels generated by various sources were measured under their normal operating conditions.

The measurements were carried out in accordance with the standard SR 6161-1:2022, "Acoustics in buildings – Part 1: Determination of noise levels in civil buildings and urban areas. Determination methods".

The values obtained by measuring the noise level during the operation of various sources within enclosed spaces are given in Table 1.

Table 1 Noise measurements results

	Noise source	Noise level [dB]	
		in the room with the source	in the next room
1	washbasin faucet	67.43	39.64
2	water falling into the bathtub	79.92	55.51
3	filling the toilet bowl	40.20	36.07
4	emptying the toilet bowl	70.55	39.61
5	radio receiver	59.95	45.73
6	television	53.04	45.22
7	air conditioning system	35.61	25.71
8	apartment heating boiler	38.83	28.68
9	refrigerator	43.37	27.04
10	walking on the floor	32.64	29.70
11	walking up and down stairs	44.19	32.89
12	ventilation system	55.45	29.59

The measurements were performed using equipment that meets the specifications for sound level meters set out in IEC 61672-1 and IEC 61672-2. Thus, the 2250 handheld sound analyzer was used, and prior to the start of measurements, it was calibrated using the Type 4231 acoustic calibrator, both manufactured by Brüel & Kjær.

For some of the investigated noise sources, the following are presented in the figures below: time-variation diagrams, spectral diagrams, and statistical distribution diagrams.

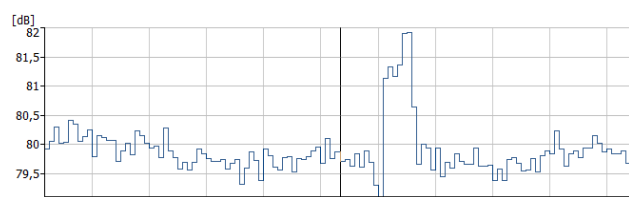


Fig. 1 Time-variation of the noise level for water falling into the bathtub

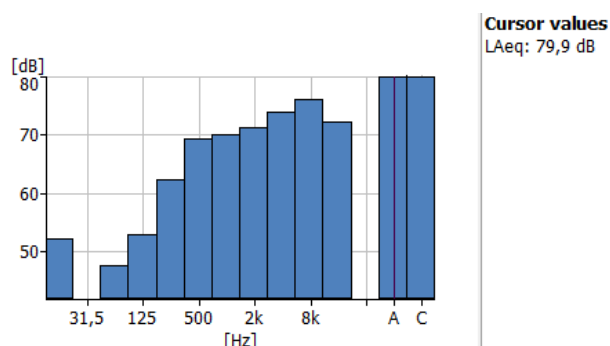


Fig. 2 Spectral diagram for water falling into the bathtub

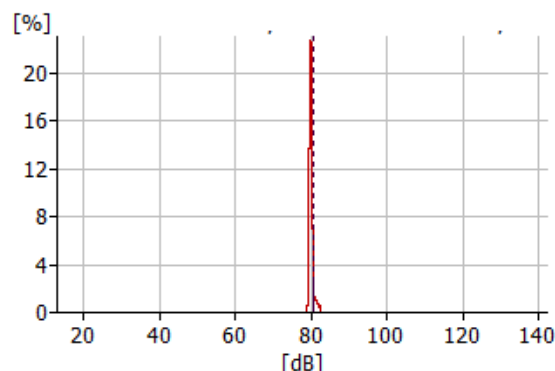


Fig. 3 Statistical distribution diagram for water falling into the bathtub

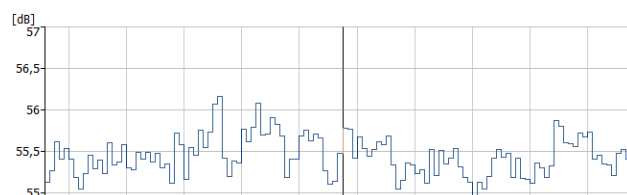


Fig. 4 Time-variation of the noise level for ventilation system

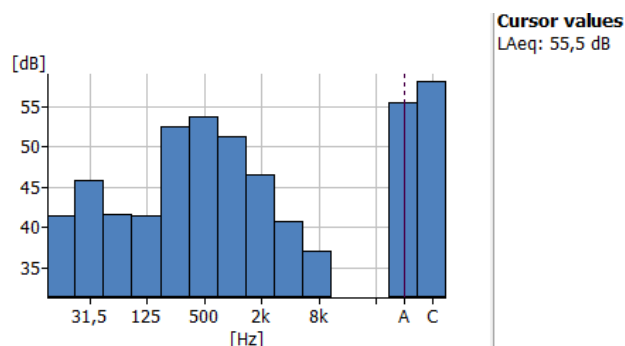


Fig. 5 Spectral diagram for the ventilation system

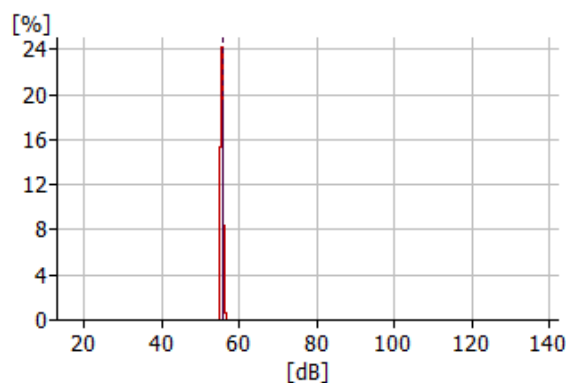


Fig. 6 Statistical distribution diagram for the ventilation system

Similarly, Table 2 presents the measured noise level values and those corresponding to the Cz30 noise curve in octave bands for noise generated by sources within an enclosed space.

Table 2 Spectral distribution in frequency bands

	16Hz	31.5Hz	63Hz	125Hz	250Hz	500Hz	1kHz	2kHz	4kHz	8kHz
Cz30	75.8	59.2	48.1	39.9	34.0	30.0	26.9	24.7	22.9	
1	57.9	52.1	50.3	49.3	48.8	55.0	58.3	62.5	61.2	58.1
2	52.1	41.7	47.4	52.9	62.4	69.4	70.0	71.4	74.0	76.0
3	48.9	40.1	49.8	37.9	36.6	34.2	33.1	34.3	32.2	28.4
4	52.3	44.5	61.8	60.3	64.2	66.3	65.0	64.3	61.6	57.1
5	44.9	38.2	39.2	35.1	42.6	56.2	56.1	50.3	52.1	44.1
6	45.6	41.7	38.1	40.0	48.8	52.7	48.8	42.0	40.3	30.9
7	52.0	36.6	36.0	38.8	39.2	33.6	30.1	23.9	20.0	16.9
8	51.8	40.6	39.2	40.5	42.2	37.6	32.9	27.5	23.2	18.5
9	41.8	36.3	39.3	45.5	49.9	39.9	30	25.3	23.5	20.1
10	48.7	40.7	41.7	32.6	31.6	28.4	24.7	25.1	25.4	22.8
11	51.9	42.0	42.8	44.5	40.9	42.3	40.0	35.5	30.3	26.0
12	41.5	45.9	41.8	41.5	52.6	53.7	51.3	46.6	40.8	37.1

5. ENSURING ACOUSTIC COMFORT IN ENCLOSED SPACES

An analysis of the noise level values generated by various sources, based on the experimental measurements presented in the previous section, reveals that, in many cases, these values exceed permissible limits; furthermore, the presence of noise causes acoustic discomfort for humans. To remedy this situation and ensure acoustic comfort in the indoor living environment where people spend their lives, it is necessary to implement measures that reduce the presence and level of noise.

The issue of achieving acoustic comfort in enclosed spaces must be viewed from two perspectives [1,2,3]:

- reducing the sound power of noise sources by incorporating acoustic parameters into manufacturing specifications

- ensuring adequate acoustic comfort through structural measures, taking into account the limits within which a person is not disturbed by noise.

When establishing noise mitigation methods for enclosed spaces, it must be taken into account that the noise penetrating these areas generally originates from both sources inside the building and external sources.

Given the diversity of these sources and the difficulty of controlling them, prescribing measures to ensure compliance with permissible limits is quite challenging.

Regarding the enclosed space itself, in order to ensure adequate acoustic comfort, defined by noise level limit values, consideration must be given to the potential for attenuating noise transmission through building elements.

Specifically, acoustic comfort requirements translate into requirements concerning the sound insulation capacity of the building elements enclosing the space.

A general conclusion supporting the focus on ensuring acoustic comfort is that a quiet environment reduces stress and improves concentration and rest.

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ACOUSTIC COMFORT IN HOSPITALITY ARCHITECTURE: ARCHITECTURAL INTEGRATION OF ACOUSTIC WALL PANELS IN HOTEL AND RESORT INTERIORS

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Abstract. *Acoustic comfort is an important component of guest experience in hotels and resorts, where rooms, restaurants, conference spaces, lobbies, and wellness facilities have different acoustic requirements. This paper reviews the architectural integration of acoustic wall panels using selected research, standards, and technical documentation. It examines material properties, mounting conditions, panel placement, and their relationship with reverberation, speech intelligibility, and interior design. The reviewed evidence indicates that performance depends on room characteristics and operating conditions, so laboratory absorption ratings cannot be translated directly into universal noise reduction values. Particular attention is given to spa and wellness areas, distinguishing dry rooms from swimming pool environments that require suitable materials and mounting systems. A design framework connects problem identification, acoustic objectives, panel selection, maintenance requirements, and outcome assessment. The review highlights opportunities and limitations of wall panels and the need for further measurements in hotel settings, supported by guest and staff evaluations.*

Key words: *Acoustic comfort, Noise control, Hospitality architecture, Acoustic wall panels, Interior acoustics, Hotel and resort design*

absorption, and vocal effort is particularly important: higher background sound levels may encourage guests to speak louder, further increasing the acoustic load [2].

Restaurant studies associate acoustic conditions with spatial experience and communication effort [3,4]. For architectural design, this means coordinating acoustic treatment with the functional organisation of the interior. Wall panels also allow surfaces to be articulated through colour, texture, and rhythm, but their location and coverage require an acoustic rationale [5].

This paper examines the opportunities and limitations of integrating acoustic wall panels into hotels and resorts. It draws on a narrative review of selected journal and conference papers, standards, and technical documentation. Research sources inform the interpretation of acoustic phenomena and intervention outcomes, while manufacturers' documentation describes configurations and conditions of use. The review is not systematic and includes no original measurements. Findings from other building types are considered in terms of their relevance to hotel facilities, with the differences explicitly acknowledged.

1. INTRODUCTION

Acoustic comfort is an important aspect of the quality of a stay in hotels and resorts. A single building accommodates rest, conversation, dining, work, and recreation, each with different requirements. Guest rooms require conditions suitable for rest and protection from unwanted sound, while restaurants, lobbies, and conference rooms require clear and effortless communication. Wellness facilities combine the need for a quieter atmosphere with maintenance requirements and, in some areas, elevated humidity.

Noise in hotel interiors may originate from building services, outdoor traffic, adjacent rooms, and occupants' activities [1]. Sound-absorbing wall panels primarily affect reflected sound within a room. Their role should therefore be defined within an overall acoustic strategy that also addresses sound transmission and source control. In restaurants, the relationship between occupancy,

2. ACOUSTIC COMFORT IN HOTELS AND RESORTS

2.1. Sound sources and functional requirements

Acoustic comfort depends on the relationship between sound sources, the room, and users' expectations. Conversation that forms part of a restaurant's atmosphere may be disturbing in an adjacent guest room or relaxation area. Before selecting a treatment, it is therefore necessary to establish whether the problem arises from reflections within the room, sound transmission from other spaces, or direct exposure to a source. The hotel room study by Nering et al. [1] highlights the importance of considering different noise sources when assessing comfort in accommodation units.

In restaurants and lobbies, simultaneous conversations among several groups create a changing acoustic environment. Rindel [2] examines the relationship between

room volume, reverberation time, occupancy, and verbal communication. This suggests that increasing seating capacity also requires reassessing acoustic conditions. In conference rooms, the priority is the transmission of speech to listeners, with architectural treatment coordinated with any sound reinforcement system.

For spa and wellness facilities, it is useful to consider dry treatment and relaxation rooms, circulation areas, and swimming pool halls separately. This distinction does not predetermine an acoustic target, but allows material exposure conditions to be considered early alongside sound sources and spatial organisation.

2.2. Acoustic indicators and user experience

Reverberation time characterises sound decay after a source stops, sound level describes acoustic conditions over a given interval and at a given location, and the Speech Transmission Index (STI) evaluates speech transmission. These indicators are not interchangeable. A reduction in reverberation time does not imply an equivalent percentage reduction in sound level, nor does it alone guarantee the desired speech intelligibility under all operating conditions [2,5,6].

Comparisons should distinguish between measurements in unoccupied rooms and measurements during use. Occupancy, vocal effort, music, and building services affect sound levels during operation. Such measurements have direct practical value, but the conditions must be documented to interpret changes correctly.

Subjective assessment complements technical measurements. Steffens et al. [3] investigate relationships between room acoustics, soundscape, and non-acoustic factors in restaurant experience. Following ceiling treatment, Tarlao et al. [4] report more favourable ratings and reduced vocal and listening effort. These findings support including user experience in intervention assessment while maintaining the distinction between treatment types.

3. ACOUSTIC WALL PANELS AND APPLICATION PRINCIPLES

3.1. Panel materials and construction

Sound-absorbing wall systems encompass different materials and constructions. In porous and fibrous absorbers, sound energy dissipation is associated with air movement through the material structure. Performance depends on physical properties, thickness, and installation, so the base material alone is insufficient to predict acoustic performance [7]. Examples include panels with a fibrous core and textile facing, as investigated by Mathiesen et al. [6], and shaped PET felt products, including ARCHISONIC Felt by Impact Acoustic [8].

Perforated and slotted systems combine a surface lining with a cavity and, depending on the configuration, an additional absorptive layer. Song et al. [9] demonstrate the significance of perforation geometry and construction parameters for the absorption response of perforated wooden panels. Visually similar linings may therefore have different acoustic properties. Knauf Cleanco is an example

of a perforated gypsum system for which the cited product documentation also includes interior wall applications [10].

Wood wool panels and systems with an additional mineral wool layer offer a different construction and visual character. In the reviewed Knauf brochure, HERADESIGN Wallcoustic Element is described as an assembly comprising a wood wool board and an additional absorptive layer [11]. Comparing such an assembly with a thin lining or textile-faced panel requires data for the actual installation rather than a comparison of surface finishes alone.

3.2. Sound absorption and mounting conditions

ISO 354 specifies laboratory measurement of sound absorption in a reverberation room, while ISO 11654 addresses the rating of sound absorption for building applications [12,13]. Declared values relate to the tested specimen and mounting conditions. An absorption coefficient or absorption class does not specify how many decibels the sound level will decrease in a proposed interior.

Selection should consider frequency-dependent data, thickness, backing, and any air gap. Changes to these parameters may alter the acoustic response [7,9]. For discrete elements, it is also important to check whether results are expressed as an absorption coefficient or an equivalent sound absorption area per element, to avoid comparing different quantities.

3.3. Placement and service requirements

Cucharero et al. [5] show that the placement of the same quantity of absorptive material affects room acoustic parameters. Panel layout should therefore be considered in relation to room geometry, other finishes, and occupant positions. Results from a particular experimental space do not establish a universal rule for optimal absorber placement in every hotel.

Architectural integration involves lining continuity, modularity, joint detailing, access to services, and the replacement of damaged elements. Surface finishes must meet maintenance needs and anticipated exposure conditions. Fire performance and moisture resistance should be checked for the specific product and assembly, without transferring declarations between different systems supplied by the same manufacturer.

Sustainability requires an assessment broader than recycled content alone. Buratti et al. [14] examine the environmental and acoustic characteristics of panels incorporating recycled materials. For hotel applications, material origin should be considered alongside durability, maintenance, and replacement. Recycled feedstock alone does not establish an overall environmental advantage or suitability for all operating conditions.

4. INTEGRATION INTO DIFFERENT HOTEL SPACES

4.1. Restaurants and lobbies

In restaurants, wall panels may be incorporated into perimeter walls and surfaces near seating areas, subject to

assessment of the available area and sound field. Their arrangement should be coordinated with table layout and existing ceiling treatment. In lobbies, reception, waiting, circulation, and informal conversation areas also require consideration. These possibilities are design suggestions rather than predetermined optimal positions. Examples of acoustic treatment integrated into hotel restaurant and lobby interiors are shown in Figs. 1 and 2.



Fig. 1 Acoustic ceiling and column treatment in Piazza restaurant, Vrdnik (source: SuperProstor / Impact Acoustic [18]).



Fig. 2 Acoustic ceiling treatment in the reception area of Palazzo di Varignana (source: Caruso Acoustic [19]).

A commercial case study of the Luminary Hotel describes the installation of 18 fabric-wrapped wall panels in the Workshop Culinary Theater [15]. It illustrates the integration of panels into the interior and the use of colour as part of its visual identity. As comparable measurements before and after installation are not reported, the example is not used as evidence of a specific noise reduction.

4.2. Conference rooms

In conference spaces, the selection of wall surfaces should be related to the positions of speakers, listeners, and sound reinforcement sources. The choice between continuous perforated linings and discrete fibrous panels depends on the acoustic objective, available surface area, and interior organisation [5,8,10]. Treatment must be coordinated with projection surfaces, doors, and equipment so that technical elements do not compromise the intended absorptive area.

Multipurpose use requires consideration of different seating arrangements and activities. A solution suited to a lecture may not be equally appropriate for a banquet or an event with music. Acoustic objectives should therefore reflect the actual room program rather than its designation alone.

4.3. Guest rooms and circulation areas

In guest rooms, wall panels may form part of a headboard or work-area lining where control of internal reflections is needed. These possibilities should not be equated with improved sound insulation between rooms. Where the dominant disturbance is sound transmitted through partitions or doors, or noise from building services, the intervention must address the relevant transmission path or source [1].

In corridors, absorptive surfaces should be coordinated with doors, signage, and circulation routes. Alongside acoustic objectives, relevant criteria include resistance to contact and impact, cleaning, and circulation safety. Wall treatment does not replace assessment of the details that affect sound transmission from corridors into guest rooms.

4.4. Spa and wellness areas

Dry relaxation and treatment rooms offer opportunities to combine acoustic panels with materials that convey warmth and a calm visual character. Their use requires consideration of actual humidity, cleaning procedures, and sound sources. Swimming pool halls constitute a separate case because of the exposure conditions affecting materials and supporting components. Illustrative ceiling configurations in spa and indoor pool interiors are shown in Figs. 3–5. The image source does not identify the installed products or establish their acoustic performance [20].



Fig. 3 Suspended ceiling elements in an indoor pool hall, Fruške Terme (source: Eventlin [20]).



Fig. 4 Ceiling panels in a spa relaxation area, Fruške Terme (source: Eventlin [20]).



Fig. 5 Ceiling configuration in a family pool area, Fruške Terme (source: Eventlin [20]).

Technical documentation demonstrates the importance of selecting a complete system. The reviewed Knauf brochure explicitly states that HERADESIGN Wallcoustic Element is not suitable for indoor swimming pools or thermal baths [11]. This restriction concerns that product and does not constitute an assessment of the entire Knauf range. Documentation for Ecophon Akusto Wall C Akutex HS provides for swimming pool applications with the appropriate Connect Thinline system [16]. Suitable confirmation of pool use was not established for the Impact Acoustic products considered here; these are used as examples of wall lining design and material expression [8].

The declared moisture resistance of a panel alone is insufficient for system selection. Surface finishes, profiles, fixings, and the intended maintenance regime must also be checked. This allows acoustic treatment to become part of a technically coordinated interior.

Table 1 summarises the criteria for integrating wall panels across hotel spaces.

Table 1 Summary of criteria for wall panel integration

Space	Acoustic focus and additional criteria
Restaurants and lobbies	Conversation and reflected sound. Seating layout, maintenance, visual identity.
Conference rooms	Speech transmission. Sound reinforcement, equipment, changes in use.

Space	Acoustic focus and additional criteria
Guest rooms	Internal reflections and sources of disturbance. Separate assessment of sound insulation and building services.
Circulation areas	Reflections associated with occupant activities. Impact resistance, cleaning, circulation safety.
Dry wellness areas	Conditions for conversation and rest. Humidity, cleaning procedures, material selection.
Swimming pool halls	Reverberation control. Demonstrated suitability of the complete system for pool use.

5. DISCUSSION

5.1. Measured outcomes and their interpretation

The study by Mathiesen et al. [6] provides the most direct example of wall treatment among the sources reviewed. Following the installation of four 120×120 cm panels in a hospital dining room, reverberation time in the unoccupied room decreased from 0.97 to 0.63 s, while STI increased from 0.604 to 0.676. The average A-weighted sound level during lunch was 64.49 dB(A) in the baseline phase and 62.47 dB(A) in the acoustic-treatment phase. The approximately 2 dB difference was recorded during use, under conditions also influenced by occupants and their activities. It therefore cannot be attributed exclusively to the panels or transferred to a hotel restaurant as a guaranteed reduction.

Table 2 compares the selected research findings and their limits of applicability.

Table 2 Selected research findings and limits of applicability

Source and treatment	Finding and limitation
Wall panels in a dining room [6]	T: $0.97 \rightarrow 0.63$ s STI: $0.604 \rightarrow 0.676$ Level: $64.49 \rightarrow 62.47$ dB(A) Different building use; sound levels during meals also depend on occupants.
Changes in absorber placement [5]	The same quantity of material produces different outcomes with different layouts. Experimental conditions; no universally optimal location.
Restaurant ceiling treatment [4]	More favourable ratings and reduced vocal and listening effort. User assessments; not evidence of wall panel performance in dB.
45 suspended elements in a pool hall [17]	Average reverberation time: $3.1 \rightarrow 2.0$ s. Suspended elements; non-peer-reviewed conference paper.

The results in the table represent different forms of evidence. Experimental changes in absorber placement [5] help explain layout effects, while user-experience research [4] demonstrates the value of subjective assessment. The swimming pool study [17] concerns suspended elements and therefore has a supporting role in the discussion of humid environments. These findings cannot reasonably be combined into an average measure of wall panel effectiveness.

Transferring findings from a hospital dining room to a hotel requires consideration of volume, existing finishes, occupancy, and activities. The relationship between absorption and vocal effort in restaurants [2] further explains why operational sound levels are not a simple property of an installed product. Intervention assessment can usefully combine measurements under controlled conditions with measurements and questionnaires during use.

5.2. A framework for selection and integration

Based on the reviewed sources, a sequence of design decisions is proposed to connect an acoustic problem with a verifiable outcome. First, the dominant disturbance is identified, distinguishing internal reverberation from sound transmission or direct exposure to a source. An objective is then defined according to the intended use: supporting conversation, speech transmission, or conditions for rest.

The next step is to select absorption characteristics, coverage, and layout, while checking mounting requirements. The architectural solution is developed alongside maintenance, durability, and equipment-access requirements. Following installation, relevant indicators are assessed, documenting occupancy and activities when measurements are taken during operation. This sequence is a synthesis intended to support design rather than an independently validated experimental model.

The visual character of panels contributes to their acceptance within an interior but does not establish acoustic quality. Similarly, high laboratory absorption does not establish suitability for a swimming pool, an area requiring intensive cleaning, or an exposed circulation route. Design decisions require a combined assessment of acoustic performance, spatial integration, and service conditions.

5.3. Contribution and limitations

The paper connects acoustic indicators and treatment findings with the conditions governing wall panel use across different hotel facilities. The proposed framework supports product selection based on intended use and a specific problem. Particular attention is given to the distinction between dry wellness rooms and swimming pool halls, which affects the selection of both panels and mounting systems.

Limitations arise from the narrative nature of the review, differences in the methods used by the studies examined, and the limited number of direct investigations of wall panels in hotels within the reviewed material. Technical documentation and commercial examples illustrate applications rather than replace independent performance measurements. The paper therefore does not provide universal noise reduction values, prescribed wall coverage percentages, or a ranking of manufacturers.

Further research should focus on comparable measurements before and after interventions in hotel restaurants, conference rooms, and wellness facilities. Documenting frequency-dependent results, panel area and placement, occupancy, and operating conditions,

supplemented by guest and staff assessments, would support more reliable design guidance.

6. CONCLUSION

Acoustic wall panels are a relevant element of hotel and resort design where reflections and prolonged reverberation hinder communication and compromise conditions for occupancy. The reviewed literature supports the potential to improve acoustic indicators and user experience through appropriate absorptive treatment. Outcomes depend on room characteristics, panel area and placement, mounting, and patterns of use.

Solutions should be selected according to the dominant problem and intended function. Restaurants and conference rooms require support for verbal communication, while guest rooms and relaxation areas also require attention to building services and sound transmission between spaces. In spa and wellness facilities, acoustic requirements must be coordinated with humidity, maintenance, and the suitability of the complete system.

Architectural integration connects these requirements with spatial organisation, materials, and interior identity. The proposed framework comprises problem identification, objective setting, panel selection and placement, assessment of service conditions, and outcome evaluation. More specific guidance requires further hotel and resort studies that connect technical measurements with user experience.

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COMPARATIVE EVALUATION OF C_{80} PREDICTION MODELS IN A SMALL LECTURE HALL USING RIR-DERIVED EXPERIMENTAL VALUES

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Abstract. *This paper presents a comparative evaluation of the Barron–Lee and Gao models for predicting the clarity index C_{80} in the A2 lecture hall at the Academy of Applied Technical and Preschool Studies, Niš, Serbia, to assess their applicability to a small lecture hall with a short reverberation time. Predictions at 500 Hz and 1000 Hz were compared with experimental values derived from measured room impulse responses. The analysis included the spatial distribution of C_{80} , linear regression as a function of source–receiver distance, model deviations, and root-mean-square errors. Both models yielded nearly identical predictions and showed decreasing trends with increasing source–receiver distance, but their predictions did not follow the experimental variations in C_{80} among individual measurement positions. The Gao model had a slightly lower RMSE than the Barron–Lee model at the frequencies analysed. Both models showed better overall agreement with the experimental values at 1000 Hz.*

Key words: *Room acoustics, Clarity index C_{80} , Room impulse response, Prediction models, Spatial variability*

1. INTRODUCTION

The acoustic quality of an enclosed space largely depends on the temporal and spatial distribution of sound energy. Direct sound, early reflections, and late reflections have different effects on sound clarity and perceived reverberance. The energies of these components are determined by analysing room impulse responses (RIRs) and are subsequently used to calculate the corresponding energy-based acoustic parameters, including the clarity index C_{80} [1].

Models developed for predicting energy-based acoustic parameters rely on different assumptions regarding the formation and distribution of reflected sound energy. The classical foundation is provided by Sabine’s statistical model from 1922 [2]. This model relates reverberation time to room volume V and the total equivalent absorption area, assuming a diffuse sound field and a spatially uniform distribution of reverberant sound energy. However, impulse-response and steady-state measurements in concert halls have shown that reflected sound energy decreases as the source–receiver distance increases [3]. Based on these findings, Barron and Lee developed a

revised model for the distribution of sound energy in concert halls in 1988 [3]. In this model, the energy at a receiver position is divided into direct, early reflected, and late reflected components. Unlike in Sabine’s model, the reflected components are not assumed to be spatially uniform; instead, their magnitudes decrease with increasing source–receiver distance r . Based on the components modelled in this manner, the clarity index C_{80} is predicted by comparing the sound energy arriving within the first 80 ms with the energy arriving thereafter. In 2007, Cabrera retained this parameter and applied the Barron–Lee model to rooms of different volumes, including rooms considerably smaller than concert halls [4]. Using measured reverberation-time values and assuming that the source–receiver distance is proportional to a linear dimension of the room, Cabrera showed that C_{80} decreases as V increases. He considered this relationship as a possible explanation for the negative correlation between C_{80} and the auditory perception of room size observed in earlier experiments involving listeners [4]. In 2020, based on RIRs measured in unoccupied multipurpose halls with proscenium stages, Gao et al. demonstrated the limitations of applying the Barron–Lee model to spaces with shorter reverberation times: the model predicts higher early and late reflected energy than that obtained from the measurements [5]. To address this limitation, in 2025 they proposed a semi-analytical model incorporating an empirically determined spatial attenuation coefficient ξ , which describes a more pronounced decrease in reflected energy with distance than that predicted by the Barron–Lee model [6].

Although the Barron–Lee model has also been considered for rooms of smaller volume, the applicability of this model and the more recent model proposed by Gao for predicting C_{80} and its spatial dependence in small lecture halls with short reverberation times remains insufficiently investigated.

The aim of this paper is to comparatively evaluate the Barron–Lee and Gao models for predicting C_{80} in the A2 lecture hall at the Academy of Applied Technical and Preschool Studies, Niš, Serbia, in the octave bands centred at 500 Hz and 1000 Hz. The evaluation is based on a

comparison of the model predictions with experimental values derived from measured RIRs. The prediction accuracy of each model was assessed from the deviations and root-mean-square error values, while linear regression analysis $C_{80} = f(r)$ was used to compare the dependence of model predictions and experimental values on source-receiver distance.

2. C_{80} PREDICTION MODELS

A key issue in the analytical prediction of C_{80} is the modelling of sound energy. Among the models based on this approach, the Barron-Lee (BL) and Gao models represent successive stages in the development of an analytical description of sound-energy distribution in rooms.

2.1. BL Model

The BL model was developed from measurements of objective acoustic quantities conducted under unoccupied conditions in concert halls and multipurpose halls used for music [3]. The model is based on the decomposition of sound energy at a receiver position into direct, early reflected, and late reflected components.

According to this model, the clarity index C_{80}^{BL} (dB) is determined using the following expression [3,4]:

$$C_{80}^{\text{BL}} = 10 \log \left(\frac{d + e_r}{l} \right), \quad (1)$$

where d is the direct sound energy, e_r is the early reflected energy, and l is the late reflected energy. Their values are calculated using the following expressions:

$$d = \frac{100}{r^2}, \quad (2)$$

$$e_r = \frac{31200T}{V} e^{-\frac{0.04r}{T}} \left[1 - e^{-\frac{1.11}{T}} \right], \quad (3)$$

and

$$l = \frac{31200T}{V} e^{-\frac{0.04r}{T}} e^{-\frac{1.11}{T}}. \quad (4)$$

In Eqs. (2) – (4), r is the source–receiver distance (m), V is the room volume (m^3), and T is the reverberation time (s). The quantities d , e_r and l are normalised with respect to the direct sound energy at a distance of 10 m [3]. The term $e^{-\frac{0.04r}{T}}$ describes the decrease in reflected energy with distance, while $e^{-\frac{1.11}{T}}$ separates the reflected energy into early and late components relative to the 80 ms temporal boundary. Consequently, spatial dependence in the BL model is represented solely by the distance r , without explicitly accounting for room geometry or individual reflection paths.

2.2. Gao Model

The semi-analytical Gao model was developed from measurements conducted under unoccupied conditions in multipurpose performance halls with proscenium stages [5,6]. It retains the BL model's division of sound energy at a receiver position and its 80-ms temporal boundary, while the spatial decay of reflected energy is described by the attenuation coefficient ξ . In the initial formulation, separate coefficients ξ_e and ξ_l were introduced for early and late reflected energy, respectively. Since their values are approximately equal and show no significant dependence on either frequency or reverberation time, the mean value $\xi = 0.068 \text{ m}^{-1}$ was adopted for general prediction [5,6]. The clarity index C_{80}^{Gao} is determined using the following expression:

$$\begin{aligned} C_{80}^{\text{Gao}} &= 10 \log \left(\frac{d + e_{r,\xi}}{l_\xi} \right) \\ &= 10 \log \left[\frac{V}{312Tr^2} e^{\left(\xi r + \frac{1.11}{T} \right)} + e^{\frac{1.11}{T}} - 1 \right], \end{aligned} \quad (5)$$

where d is the direct sound energy, as in the BL model, while $e_{r,\xi}$ and l_ξ denote the early and late reflected energy, respectively.

3. EXPERIMENT

Measurements were conducted under unoccupied conditions in lecture hall A2 at the Niš Department of the Academy of Applied Technical and Preschool Studies (Fig. 1), with the aim of determining C_{80} values from the measured RIRs and comparing them with those predicted by the models.

The room is rectangular in plan, with internal dimensions of $10.95 \times 10.74 \text{ m}$, a stepped floor, and a suspended ceiling. Its height is approximately 3.19 m, and its volume is about 375 m^3 . The lecture hall contains 135 seats arranged in nine rows.

The experimental procedure included the following steps:

Step 1 – Source and measurement positions. The position of the sound source S and those of the nine measurement points (MP1 – MP9) in the lecture hall are shown in Fig. 2 (the first row of seats, which has no desk in front of it, is not shown). The source–receiver distance was determined for each MP.

Step 2 – RIR measurement. The following equipment was used for the RIR measurements: a PCB 130D20 omnidirectional microphone with a 7-mm diaphragm, a B&K 4295 omnidirectional sound source (dodecahedral loudspeaker), a B&K 2716-C audio power amplifier rated at 100 W RMS, and a laptop computer with an integrated SoundMAX Integrated Digital Audio sound card (Analog Devices). The RIRs were measured using a 6 s sinusoidal sweep signal at a sampling frequency of $f_s = 44.1 \text{ kHz}$ and recorded using EASERA software.



Fig. 1 Lecture hall A2

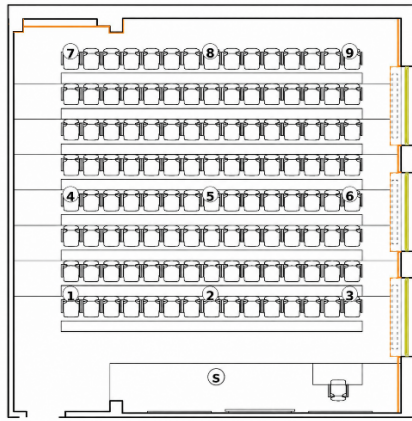


Fig. 2 Plan of room A2 showing the RIR measurement arrangement: S – sound source position, 1–9 – receiver positions

Five measurements were performed at each MP, yielding a total of 45 RIRs in WAV format. The air temperature was $t = 25.3$ C.

Step 3 – RIR processing and determination of C_{80}^{RIR} .

The recorded RIRs were processed and the C_{80} values were calculated in MATLAB for the octave bands centred at 500 Hz and 1000 Hz. For each of the five RIRs recorded at each MP: a) the C_{80} was determined, after which the mean value for that MP, denoted by C_{80}^{RIR} was calculated, and b) the $T_{20,f}$ value was determined, after which the mean value for that MP was calculated. Based on the mean values for all nine MPs, the overall mean value $\overline{T_{20,f}}$ was determined for each frequency band considered.

Step 4 – Calculation of C_{80} using the theoretical prediction models. For each MP, C_{80} values were calculated using the expressions given in Section 2. The corresponding geometrical data and the spatially averaged reverberation time values determined in Step 3 were used in the calculations. The resulting values were denoted by C_{80}^{BL} and C_{80}^{Gao} .

Step 5 – Linear regression analysis. Linear regression analysis of the dependence on distance r was performed for C_{80}^{RIR} , C_{80}^{BL} and C_{80}^{Gao} separately at 500 Hz and 1000 Hz. The regression lines were expressed as $C_{80} = a + br$.

The following were determined: a) the y-intercepts a_{RIR} , a_{BL} and a_{Gao} , b) the slopes of the regression lines b_{RIR} , b_{BL} and b_{Gao} , and c) the corresponding coefficients of determination R_{RIR}^2 , R_{BL}^2 and R_{Gao}^2 .

Step 6 – Analysis of deviations and errors. For each MP and both frequencies considered, the deviations between the experimental values C_{80}^{RIR} and the values obtained using the prediction models, C_{80}^{pred} , were determined:

$$\Delta C_{80}^{\text{pred}} = C_{80}^{\text{RIR}} - C_{80}^{\text{pred}}. \quad (6)$$

A negative value of $\Delta C_{80}^{\text{pred}}$ indicates that the predicted value is higher than the corresponding C_{80}^{RIR} value, whereas a positive value indicates that it is lower. For each model and frequency considered, the mean deviation across all nine MPs, $\overline{\Delta C_{80}^{\text{pred}}}$, and the root-mean-square error (RMSE) were determined:

$$\text{RMSE} = \sqrt{\frac{1}{9} \sum_{i=1}^9 (\Delta C_{80,i}^{\text{pred}})^2}. \quad (7)$$

Based on the procedure described above, a comparative analysis of the experimental and model-predicted C_{80} values was performed, and the results are presented in tabular and graphical form.

3.1. Results and analysis

The model-predicted values were calculated using the spatially averaged reverberation times $\overline{T_{20,500}} = 0.456$ s and $\overline{T_{20,1000}} = 0.521$ s. The corresponding source-receiver distance r_i was used for each MP.

3.1.1. Spatial distribution of C_{80}^{RIR} and comparison with BL and Gao model predictions

The simulated spatial distributions of C_{80}^{RIR} in the octave bands centred at 500 Hz and 1000 Hz are shown in Fig. 3. Values at the measurement positions, together with the corresponding Barron-Lee and Gao model predictions, are given in Tables 1 and 2.

Figure 3(a) shows pronounced spatial variation in C_{80}^{RIR} at 500 Hz. Values range from 5.339 dB at MP9 to 10.852 dB at MP4, a spread of 5.513 dB (Table 1). A high value of 10.525 dB was also obtained at MP8, whereas the values at the adjacent positions MP7 and MP9 are 6.840 dB and 5.339 dB, respectively. Even MP7 and MP9, which are at the same distance from the source, differ by 1.501 dB. This pattern indicates that source–receiver distance alone cannot account for the spatial variation in C_{80}^{RIR} at 500 Hz; local characteristics of the sound field may also contribute.

The BL and Gao predictions at 500 Hz, C_{80}^{BL} and C_{80}^{Gao} , are very close, differing by only 0.053 – 0.078 dB across the measurement positions (Table 1).

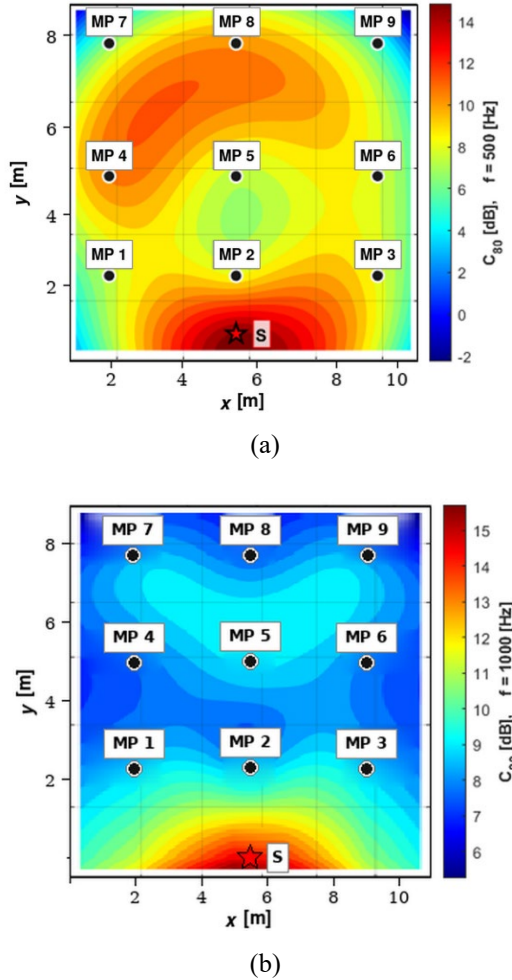


Fig. 3 Simulated spatial distributions of C_{80} based on RIR-derived data in A2 at (a) 500 Hz and (b) 1000 Hz

Both models show considerably less variation between MPs than C_{80}^{RIR} . For example, MP4 and MP6 are at the same distance from the source, so each model predicts an identical value at these two positions. In contrast, C_{80}^{RIR} is 10.852 dB at MP4 and 8.120 dB at MP6, a difference of 2.732 dB.

At 1000 Hz, the spatial distribution of C_{80}^{RIR} , shown in Fig. 3(b), is considerably more uniform than at 500 Hz. The values range from 7.671 dB at MP8 to 9.204 dB at MP5 (Table 2), giving a difference of 1.533 dB, considerably smaller than the 5.513 dB difference obtained at 500 Hz.

The predicted values of the BL and Gao models, C_{80}^{BL} and C_{80}^{Gao} , are again very close, with the differences between them at individual MPs ranging from 0.021 to 0.033 dB. Both models yield their highest value at MP2, whereas the highest C_{80}^{RIR} value is obtained at MP5. Thus, although the RIR-derived values at 1000 Hz are more spatially uniform, the models do not fully reproduce their pattern across the measurement positions.

The predictions of both models are higher than the corresponding C_{80}^{RIR} values at all nine MPs.

Table 1 Parameters used in the prediction models and the corresponding model-predicted and RIR-derived C_{80} values for A2 at 500 Hz

MP	r (m)	$f = 500$ Hz			
		$\overline{T}_{20}$ (s)	C_{80}^{BL} (dB)	C_{80}^{Gao} (dB)	C_{80}^{RIR} (dB)
1	4.2	0.456	11.096	11.029	7.701
2	2.3		12.396	12.318	8.687
3	4.2		11.096	11.029	8.425
4	6.1		10.714	10.656	10.852
5	5.0		10.889	10.827	7.620
6	6.1		10.714	10.656	8.120
7	8.5		10.525	10.472	6.840
8	7.7		10.570	10.516	10.525
9	8.5		10.525	10.472	5.339

Table 2 Parameters used in the prediction models and the corresponding model-predicted and RIR-derived C_{80} values for A2 at 1000 Hz

MP	r (m)	$f = 1000$ Hz			
		$\overline{T}_{20}$ (s)	C_{80}^{BL} (dB)	C_{80}^{Gao} (dB)	C_{80}^{RIR} (dB)
1	4.2	0.521	9.513	9.486	8.861
2	2.3		10.719	10.686	8.421
3	4.2		9.513	9.486	8.810
4	6.1		9.166	9.143	7.756
5	5.0		9.325	9.300	9.204
6	6.1		9.166	9.143	7.991
7	8.5		8.996	8.975	8.431
8	7.7		9.037	9.016	7.671
9	8.5		8.996	8.975	8.284

3.1.2. Linear regression analysis

The spatial trends of the experimental and predicted values were additionally analysed using linear regression. The regression-line parameters and coefficients of determination are presented in Table 3, while the regression lines are compared graphically in Fig. 4.

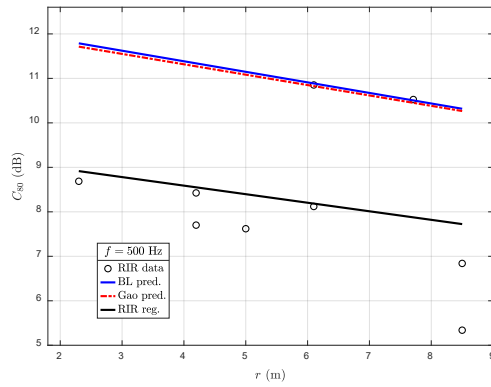
At 500 Hz, the regression lines of the BL and Gao models almost overlap, with slopes of $b_{BL} = -0.237$ dB/m and $b_{Gao} = -0.233$ dB/m, and coefficients of determination of $R_{BL}^2 = 0.744$ and $R_{Gao}^2 = 0.741$, respectively. The slopes of the BL and Gao regressions have the same sign and are similar in magnitude to the slope of the RIR regression, $b_{RIR} = -0.192$ dB/m. However, their y-intercepts, $a_{BL} = 12.334$ dB and $a_{Gao} = 12.251$ dB, are higher than the y-intercept of the RIR regression, $a_{RIR} = 9.358$ dB. Consequently, both model regression lines lie above the RIR regression line over the entire distance range considered. By contrast, the very low coefficient of determination of the RIR regression, $R_{RIR}^2 = 0.058$, indicates that the source-receiver distance explains only 5.8 % of the spatial variance in the experimental C_{80}^{RIR} values at this frequency. Therefore, the apparent agreement

between the model and RIR regression slopes should be interpreted with caution and should not be taken as evidence that the BL and Gao models reliably reproduce the measured spatial trend in C_{80} .

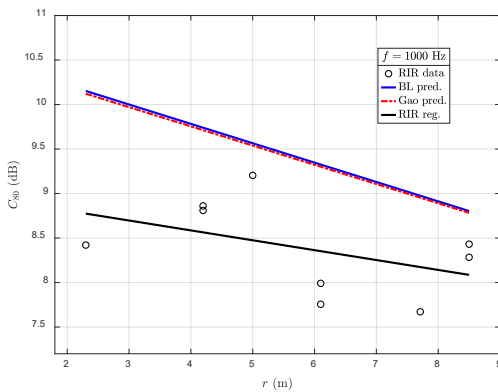
At 1000 Hz, the regression lines of the BL and Gao models again nearly overlap, with slopes of $b_{BL} = -0.218$ dB/m and $b_{Gao} = -0.216$ dB/m and coefficients of determination of $R_{BL}^2 = 0.739$ and $R_{Gao}^2 = 0.737$, respectively.

Table 3 Regression analysis and statistical parameters of model-predicted and RIR-derived C_{80} values for A2 at 500 Hz and 1000 Hz

(a) BL regression: $C_{80}^{BL} = a_{BL} + b_{BL} \cdot r$			
f (Hz)	a_{BL} (dB)	b_{BL} (dB/m)	R_{BL}^2
500	12.334	-0.237	0.744
1000	10.653	-0.218	0.739
(b) Gao regression: $C_{80}^{Gao} = a_{Gao} + b_{Gao} \cdot r$			
f (Hz)	a_{Gao} (dB)	b_{Gao} (dB/m)	R_{Gao}^2
500	12.251	-0.233	0.741
1000	10.618	-0.216	0.737
(c) RIR regression: $C_{80}^{RIR} = a_{RIR} + b_{RIR} \cdot r$			
f (Hz)	a_{RIR} (dB)	b_{RIR} (dB/m)	R_{RIR}^2
500	9.358	-0.192	0.058
1000	9.030	-0.111	0.209



(a)



(b)

Fig. 4 Regression analysis of RIR-derived and model-predicted C_{80} values at (a) 500 Hz and (b) 1000 Hz

The absolute values of these slopes are approximately twice the absolute value of the RIR regression slope, $|b_{RIR}| = 0.111$ dB/m. This relationship between the slopes indicates that both models predict a more pronounced decrease in C_{80} with distance than that determined experimentally. Their y-intercepts, $a_{BL} = 10.653$ dB and $a_{Gao} = 10.618$ dB, are higher than the y-intercept of the RIR regression, $a_{RIR} = 9.030$ dB. Consequently, both model regression lines remain above the RIR regression line over the entire distance range considered. The coefficient of determination of the RIR regression, $R_{RIR}^2 = 0.209$, is higher than at 500 Hz, but still indicates a weak linear dependence of the experimental C_{80} values on distance.

The coefficients of determination indicate the extent to which the linear dependence on distance explains the variation within each set of values, but they do not, by themselves, provide a measure of agreement between the model predictions and the RIR values. Therefore, the accuracy of the model predictions was additionally evaluated by analysing the deviations ΔC_{80} and the RMSE values.

3.1.3. Analysis of ΔC_{80}

The ΔC_{80}^{pred} values at individual MPs are presented in Table 4 for 500 Hz and in Table 5 for 1000 Hz, while their variation across the MPs is shown graphically in Fig. 5.

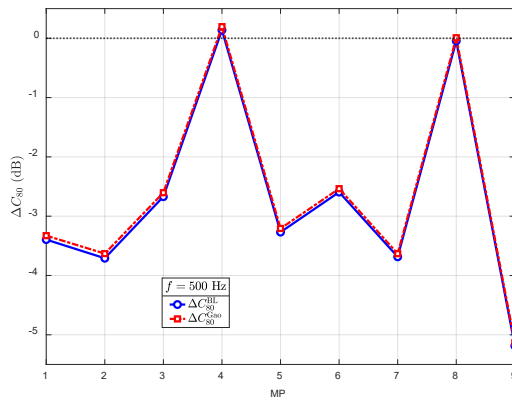
Table 4 ΔC_{80} values for A2 at 500 Hz

MP	$f = 500$ Hz	
	ΔC_{80}^{BL} (dB)	ΔC_{80}^{Gao} (dB)
1	-3.395	-3.328
2	-3.709	-3.631
3	-2.671	-2.604
4	0.138	0.196
5	-3.269	-3.207
6	-2.594	-2.536
7	-3.685	-3.632
8	-0.045	0.009
9	-5.186	-5.133
	$\overline{\Delta C_{80}^{BL}}$ (dB)	$\overline{\Delta C_{80}^{Gao}}$ (dB)
	-2.713	-2.652

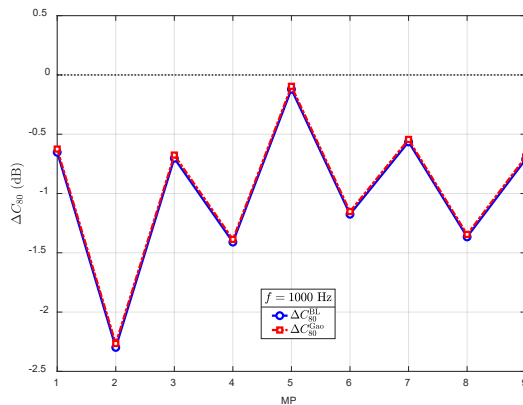
At 500 Hz, the deviations for the BL and Gao models nearly overlap at all MPs, as is clearly evident in Fig. 5(a). The ΔC_{80}^{BL} values are negative at eight MPs, whereas the ΔC_{80}^{Gao} values are negative at seven of the nine MPs. This means that the BL predictions exceed the corresponding RIR values at eight MPs and the Gao predictions at seven MPs. The mean deviations are $\overline{\Delta C_{80}^{BL}} = -2.713$ dB and $\overline{\Delta C_{80}^{Gao}} = -2.652$ dB. The largest negative deviations for both models are obtained at MP9: $\Delta C_{80}^{BL} = -5.186$ dB and $\Delta C_{80}^{Gao} = -5.133$ dB. The smallest deviations in absolute value are obtained at MP4 and MP8.

Table 5 ΔC_{80} values for A2 at 1000 Hz

$f = 1000 \text{ Hz}$		
MP	$\Delta C_{80}^{\text{BL}} \text{ (dB)}$	$\Delta C_{80}^{\text{Gao}} \text{ (dB)}$
1	-0.652	-0.625
2	-2.298	-2.265
3	-0.703	-0.676
4	-1.410	-1.387
5	-0.121	-0.096
6	-1.175	-1.152
7	-0.565	-0.544
8	-1.366	-1.345
9	-0.712	-0.691
	$\overline{\Delta C_{80}^{\text{BL}}} \text{ (dB)}$	$\overline{\Delta C_{80}^{\text{Gao}}} \text{ (dB)}$
	-1.000	-0.976



(a)



(b)

Fig. 5 Deviations between RIR-derived and model-predicted C_{80} values at (a) 500 Hz and (b) 1000 Hz

The corresponding $\Delta C_{80}^{\text{BL}}$ values are +0.138 dB and -0.045 dB, while the $\Delta C_{80}^{\text{Gao}}$ values are +0.196 dB and +0.009 dB, respectively.

At 1000 Hz, the deviations for the BL and Gao models nearly overlap at all MPs, as is clearly evident in Fig. 5(b). The $\Delta C_{80}^{\text{BL}}$ and $\Delta C_{80}^{\text{Gao}}$ values are negative at all nine MPs. This means that the predictions of both models exceed the

corresponding RIR values at every MP. The mean deviations are $\overline{\Delta C_{80}^{\text{BL}}} = -1.000 \text{ dB}$ and $\overline{\Delta C_{80}^{\text{Gao}}} = -0.976 \text{ dB}$ and are smaller in absolute value than at 500 Hz. The largest negative deviations for both models occur at MP2, where $\Delta C_{80}^{\text{BL}} = -2.298 \text{ dB}$ and $\Delta C_{80}^{\text{Gao}} = -2.265 \text{ dB}$. The smallest deviations in absolute value are obtained at MP5, where $\Delta C_{80}^{\text{BL}} = -0.121 \text{ dB}$, and $\Delta C_{80}^{\text{Gao}} = -0.096 \text{ dB}$.

Overall, the BL and Gao models yield nearly identical deviations at both frequencies. Their deviations are predominantly negative at 500 Hz and negative at all MPs at 1000 Hz, while their mean deviations are smaller in absolute value at 1000 Hz.

3.1.4. RMSE analysis

The RMSE values for the BL and Gao models at 500 and 1000 Hz are presented in Table 6.

Table 6 RMSE values of ΔC_{80} across all MPs at 500 Hz and 1000 Hz

RMSE (dB)		
$f \text{ (Hz)}$	BL	Gao
500	3.168	3.115
1000	1.168	1.146

At 500 Hz, the RMSE is 3.168 dB for the BL model and 3.115 dB for the Gao model. At 1000 Hz, the values are lower: 1.168 dB and 1.146 dB, respectively. The Gao model has a slightly lower RMSE at both frequencies, but the difference between the models is small: 0.053 dB at 500 Hz and 0.022 dB at 1000 Hz. Thus, both models show better overall agreement with the C_{80}^{RIR} values at 1000 Hz.

However, RMSE does not indicate the direction of the deviations or describe the differences among individual measurement positions. The deviation analysis showed that the predictions of both models are generally higher than the corresponding C_{80}^{RIR} values, while their nearly identical predictions at 500 Hz do not follow the pronounced changes in the experimental values from one measurement position to another.

4. CONCLUSION

This paper conducted a comparative analysis of the applicability of the Barron-Lee and Gao models for predicting C_{80} in a small lecture hall at 500 Hz and 1000 Hz. The model predictions were compared with experimental values derived from measured RIRs. The analysis considered the spatial distribution of C_{80} , its regression as a function of source-receiver distance, deviations at individual measurement positions, and RMSE values. This approach made it possible to assess both overall accuracy and the ability of the models to reproduce the spatial pattern of the experimental values.

The RIR values showed substantially greater spatial variability at 500 Hz than at 1000 Hz. The difference between the highest and lowest values was 5.513 dB at 500 Hz and 1.533 dB at 1000 Hz. At the same time, the low

coefficients of determination for the RIR regressions, $R_{\text{RIR}}^2 = 0.058$ and $R_{\text{RIR}}^2 = 0.209$, show that source–receiver distance explains only a limited part of the measured spatial variability of C_{80}^{RIR} . These results indicate a substantial influence of local sound field characteristics, particularly at 500 Hz.

The BL and Gao models produced nearly identical predictions at both frequencies. Their regression lines have negative slopes, consistent with the direction of the RIR trend, but their higher intercepts place them above the RIR regression lines throughout the distance range considered. Accordingly, their predictions are generally higher than the corresponding RIR values. At 1000 Hz, the high coefficients of determination for the BL and Gao regressions, $R_{\text{BL}}^2 = 0.739$ and $R_{\text{Gao}}^2 = 0.737$, confirm a pronounced linear dependence of their predictions on distance, but do not indicate good agreement with the RIR values.

The Gao model has a slightly lower RMSE than the BL model at both frequencies: 3.115 versus 3.168 dB at 500 Hz, and 1.146 versus 1.168 dB at 1000 Hz. Both models show better overall agreement with the C_{80}^{RIR} values at 1000 Hz.

Taken together, the regression analysis, deviations at individual measurement positions, and RMSE values show

that a pronounced dependence of model predictions on distance does not imply good agreement with C_{80}^{RIR} at every measurement position. In the small lecture hall studied, neither model adequately captures the local variation in the experimental values, particularly at 500 Hz.

Further research should assess the applicability of these models over a wider frequency range and in acoustically treated rooms of similar purpose and volume.

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FREQUENCY-DEPENDENT JOINT ASSESSMENT OF SOUND ABSORPTION AND TRANSMISSION LOSS OF ACOUSTIC MATERIALS

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Abstract. *Acoustic materials may be required to reduce both reflected and transmitted sound, but high sound absorption does not necessarily imply high transmission loss. This study presents a joint frequency-dependent evaluation of six polymeric, cellular and fibrous materials using impedance-tube measurements. Normal-incidence sound absorption coefficients were determined by the two-microphone transfer-function method, while transmission loss was obtained using the four-microphone transfer-matrix method. To compare the two acoustic functions, arithmetic band means were calculated over 500 – 1600 Hz and 2000 – 5000 Hz and represented in a joint SAC-TL performance map. The flax/polypropylene specimen showed the strongest high-frequency absorption, reaching $\alpha = 0.84$ at 5000 Hz, but only 4.3 dB transmission loss. In contrast, a cellular NBR specimen reached 37.6 dB transmission loss with $\alpha = 0.23$. Open-cell TPE specimens occupied an intermediate region. The joint map distinguishes transmission-loss-oriented, absorption-oriented and intermediate responses and provides a compact basis for comparative material screening without introducing an arbitrary combined performance index.*

Key words: *Sound absorption coefficient, Transmission loss, Impedance tube, Acoustic materials, Performance map*

1. INTRODUCTION

Noise-control materials reduce acoustic energy through reflection, transmission reduction and dissipation within porous, cellular or fibrous structures [1,2]. Materials used as exposed linings are primarily selected for absorption, whereas barriers and partitions are intended to limit transmission. In many engineering applications, however, both functions are relevant and should be considered together. This is especially important for cellular and composite materials, for which density, porosity, internal morphology and surface condition may influence the two responses differently [1,3].

Impedance-tube methods provide controlled laboratory procedures for characterising small specimens under normal-incidence plane-wave conditions. ISO 10534-2 specifies the two-microphone transfer-function method for normal-incidence sound absorption [4], while ASTM E2611 uses a four-microphone transfer-matrix approach for normal-incidence transmission loss and related material properties [5,6]. The methodological scope of impedance-tube approaches was reviewed previously by the authors [7]. Preliminary results for the material set considered here

were reported in conference publications [8,9]. The present contribution focuses on a compact quantitative comparison of the two acoustic functions and on their change between two frequency regions.

The objective is to compare sound absorption and transmission loss without combining them into a single weighted index. Arithmetic band means are evaluated over 500 – 1600 Hz and 2000 – 5000 Hz and plotted in a two-dimensional SAC-TL performance space. This representation highlights competing advantages and the frequency-dependent shift of each specimen.

Sustainable and bio-based acoustic materials are increasingly considered as alternatives to conventional synthetic absorbers [2,12-15]. Natural fibres can provide favourable dissipative behaviour, but their low mass and open structure may limit transmission reduction. Conversely, denser or closed-cell polymeric materials may provide stronger transmission loss while absorbing less incident energy. A joint representation is therefore useful when the intended component must contribute to both reflected- and transmitted-sound control.

The distinction between absorption and transmission is also important when laboratory results are transferred to practical noise-control concepts. A high absorption coefficient indicates that a small fraction of the incident energy is reflected under the specified boundary condition, but it does not by itself identify how much energy is transmitted through the specimen. Likewise, high transmission loss does not imply that the exposed surface is an efficient absorber. For this reason, the two quantities are treated independently throughout the present study and are compared only as coordinates in a joint performance space.

The investigated set was selected because it includes materials with substantially different structures and expected acoustic roles. The cellular NBR and TPE specimens represent polymeric materials with different surface and cell characteristics, whereas the flax/polypropylene specimen represents a lightweight fibrous structure. Comparing these materials within the same graphical framework provides a useful illustration of how different structural concepts can occupy different regions of the absorption-transmission-loss space.

2. MATERIALS AND METHODS

2.1. Measurement principle

For SAC measurements, the test specimen was mounted at one end of a rigid cylindrical tube and excited by a broadband stationary signal. Under plane-wave conditions, the sound field in front of the specimen is represented as the superposition of incident and reflected waves. The complex transfer function between two microphone signals provides the complex reflection coefficient, from which the normal-incidence absorption coefficient is obtained as the fraction of incident energy not reflected by the specimen [4].

For TL measurements, two microphones were positioned upstream and two downstream of the specimen. Measurements under two downstream termination conditions provide the independent data required to determine the acoustic transfer-matrix elements relating sound pressure and particle velocity at the two specimen faces [5,6]. The corresponding energy transmission coefficient is then used to calculate normal-incidence transmission loss in decibels. SAC and TL characterise different test arrangements and are therefore compared as separate descriptors rather than treated as complementary fractions of one energy balance.

2.2. Test materials

Six materials for which both sound absorption coefficient (SAC) and transmission loss (TL) results were available were included: Samples 1, 2, 3, 4, 6 and 8. The original identifiers were retained to enable comparison with earlier reporting [8,9]. The tested set comprised cellular NBR rubber, open- and closed-cell TPE materials and a non-woven flax/polypropylene material. Table 1 summarises the material descriptions, bulk densities and specimen thicknesses.

Table 1 Characteristics of the tested materials used for sound absorption and transmission loss measurements

Sample	Material description	Density [kg/m ³]	Specimen thickness [mm]
1	Cellular NBR, ground front surface	274.5	10
2	Open-cell hot-pressed TPE, high density	486.9	10
3	Open-cell hot-pressed TPE, low density	315.4	10
4	Closed-cell TPE	91.3	10
6	Cellular NBR, non-ground front surface	286.6	10
8	Non-woven flax/polypropylene	129.2	8

The same physical specimens were used for both SAC and TL measurements. Their thickness was 10 mm for Samples 1, 2, 3, 4 and 6, and 8 mm for Sample 8. Thus, the joint SAC-TL comparison for each material refers to the same specimen tested under the respective measurement configurations.

2.3. Measurement procedure and data processing

Measurements were performed using Brüel & Kjær Type 4206 and 4206-T impedance-tube configurations (Fig. 1) with PULSE Acoustic Material Testing Type 7758 software [10]. The 100 mm tube had a nominal operating range of 50–1600 Hz, and the 29 mm tube 500–6400 Hz. SAC measurements followed ISO 10534-2 [4] and used broadband random excitation at 1.414 V_{rms}, 150 averages and 2 Hz frequency resolution. TL measurements followed ASTM E2611 [5] and used random excitation at 1 V_{rms}, 1600 spectral lines and 200 averages, with frequency resolutions of 1 Hz and 4 Hz for the large- and small-tube configurations, respectively. Calibration procedures were applied to reduce amplitude and phase mismatch between microphone channels; the arrangements were based on previous verification of the same system [11].



Fig. 1 Brüel & Kjær Type 4206 and Type 4206-T impedance-tube equipment used for the measurements

SAC results from the large and small tubes were combined within their 500 – 1600 Hz overlap using a linear frequency-dependent weighting, with the large-tube contribution decreasing and the small-tube contribution increasing across the overlap. Below 500 Hz the large-tube result was used, and above 1600 Hz the small-tube result was used. The weighting is a post-processing choice and is not an uncertainty-based weighting.

The overlap treatment was introduced to avoid an abrupt change from one tube configuration to the other. Because the large and small tubes differ in diameter, microphone spacing and usable plane-wave frequency range, the overlap interval provides a region in which both configurations contribute to the reported SAC curve. Linear interpolation was applied where the underlying frequency grids differed. The resulting combined curve is used only for descriptive comparison and does not constitute an independent validation of agreement between the two tube configurations.

For the four-microphone method, the transfer-matrix formulation requires two independent downstream boundary conditions. Channel calibration was performed before material testing to reduce the effect of microphone amplitude and phase mismatch. Previous work with the same equipment examined calibration specimens and anechoic-termination arrangements and identified wedge-shaped polyurethane foam as a suitable broadband absorber for these procedures [11]. The present conference paper does not repeat that calibration study, but uses it as methodological support for the reported measurement chain.

For joint comparison, arithmetic means of the one-third-octave SAC and TL values were calculated for six bands centred at 500, 630, 800, 1000, 1250 and 1600 Hz and five bands centred at 2000, 2500, 3150, 4000 and 5000 Hz. These means are descriptive comparative quantities rather than standardised single-number ratings.

The range below 500 Hz was excluded from the interval means because all tested specimens showed generally low absorption below approximately 400 Hz and the more pronounced differences relevant to the joint comparison occurred above 500 Hz. The two selected intervals also separate the large/small-tube overlap region from the higher-frequency region measured with the small tube. No uncertainty estimates were available; consequently, small differences between interval means should not be over-interpreted.

3. RESULTS AND DISCUSSION

3.1. Frequency-dependent acoustic response

The normal-incidence sound absorption results are shown in Fig. 2. Samples 2 and 3 provided the most favourable sound absorption through much of the mid-frequency range. Sample 8 showed a distinctly different response: its absorption remained relatively low at low and mid frequencies but increased strongly above 1600 Hz, reaching 0.84 at 5000 Hz and 0.92 at 6300 Hz. Samples 1 and 4 remained comparatively weak absorbers, while Sample 6 showed intermediate but generally modest absorption.

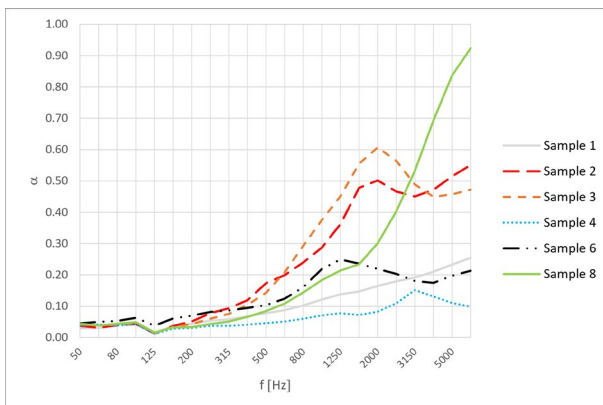


Fig. 2 Normal-incidence sound absorption coefficient of the tested materials in one-third-octave frequency bands

Among the open-cell TPE materials, Sample 3 showed the stronger mid-frequency absorption, whereas Sample 2 maintained a more nearly constant absorption level in the upper part of the investigated range. Sample 2 increased from $\alpha = 0.17$ at 500 Hz to approximately 0.5 above 1600 Hz and then remained comparatively stable, whereas Sample 3 reached the higher peak response around 2000 Hz. Sample 8 followed a different trend, increasing from $\alpha = 0.08$ at 500 Hz to 0.23 at 1600 Hz and then rising continuously to 0.84 at 5000 Hz. This contrast illustrates the strong dependence of material ranking on frequency.

Samples 1 and 4 showed comparatively weak absorption throughout the investigated range. Sample 1

increased only gradually from $\alpha = 0.08$ at 500 Hz to 0.23 at 5000 Hz. Sample 4 had the lowest overall absorption, with values around 0.05–0.07 in the 500–1600 Hz region and approximately 0.08–0.15 from 2000 to 5000 Hz. Sample 6 occupied an intermediate position, increasing to about 0.25 near 1250 Hz and remaining close to 0.20–0.24 at higher frequencies. These responses demonstrate that the materials cannot be represented adequately by a single frequency-independent absorption value.

The TL results (Fig. 3) reveal a substantially different ranking. Sample 1 exhibited the highest TL over most of the mid- and high-frequency range and reached 37.6 dB at 5000 Hz. Samples 4 and 6 also developed comparatively high TL toward the upper part of the range. Samples 2 and 3 occupied an intermediate region, whereas Sample 8 had by far the lowest TL, approximately 3–7 dB over most of the investigated range and 4.3 dB at 5000 Hz. Thus, the specimen with the strongest high-frequency absorption was the weakest transmission-loss element.

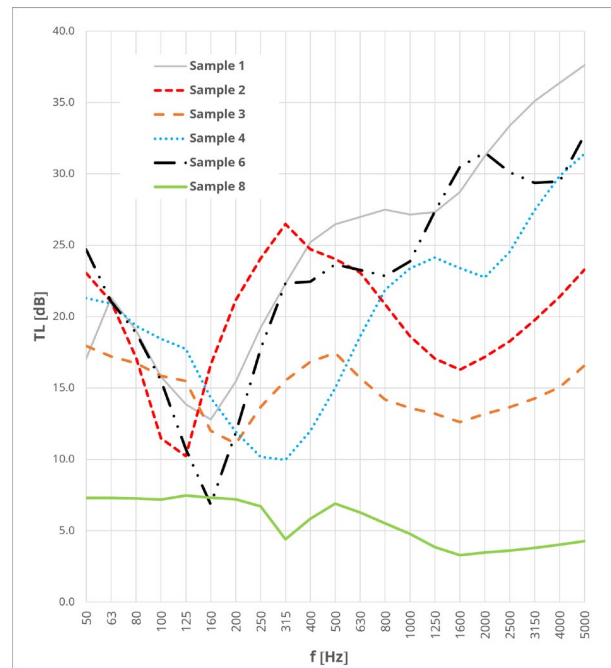


Fig. 3 Normal-incidence transmission loss of the tested materials in one-third-octave frequency bands

Sample 1 increased from 26.5 dB at 500 Hz to 28.7 dB at 1600 Hz and then to 31.3 dB at 2000 Hz, 36.4 dB at 4000 Hz and 37.6 dB at 5000 Hz. Sample 6 exhibited a pronounced low-frequency minimum near 160 Hz but increased to 30.5 dB at 1600 Hz and 32.7 dB at 5000 Hz. Sample 4 similarly increased toward higher frequencies, reaching 31.4 dB at 5000 Hz. By comparison, Sample 2 decreased from 24.0 dB at 500 Hz to 16.3 dB at 1600 Hz before increasing moderately at higher frequencies, while Sample 3 remained generally lower and smoother.

At lower frequencies, several specimens exhibited pronounced TL minima. Sample 1 reached about 12.8 dB at 160 Hz, Sample 6 about 6.8 dB at 160 Hz and Sample 4 about 10 dB at 315 Hz. Sample 2 had a minimum near 125 Hz followed by a local increase around 250–315 Hz, while Sample 3 varied more smoothly. These features are retained in the frequency-response curves but are

intentionally not condensed into the two interval means used for the performance map.

3.2. Joint SAC-TL performance

Table 2 summarises the arithmetic means used for the joint assessment. In the 500–1600 Hz region, Sample 3 had the highest mean SAC (0.34), followed by Sample 2 (0.29), while their mean TL values were 14.5 and 20.0 dB. Samples 1, 4 and 6 combined lower mean sound absorption with higher mean TL. In the 2000 – 5000 Hz region, Sample 8 reached the highest mean SAC (0.55) but retained the lowest mean TL (3.8 dB), whereas Sample 1 reached the highest mean TL (34.7 dB).

Table 2 Mean normal-incidence SAC and TL over the selected frequency regions

Sample	500 – 1600 Hz SAC / TL [dB]	2000 – 5000 Hz SAC / TL [dB]
1	0.11 / 27.4	0.19 / 34.7
2	0.29 / 20.0	0.48 / 20.0
3	0.34 / 14.5	0.51 / 14.5
4	0.06 / 21.1	0.12 / 27.2
6	0.18 / 25.3	0.19 / 30.6
8	0.16 / 5.1	0.55 / 3.8

The joint performance map in Fig. 4 makes the trade-off and its frequency dependence directly visible. Open symbols represent the 500–1600 Hz means and red symbols the 2000–5000 Hz means; arrows indicate the shift between the two regions. Movement to the right denotes higher mean absorption and upward movement higher mean TL. The map is descriptive and deliberately avoids threshold values or an arbitrary composite index.

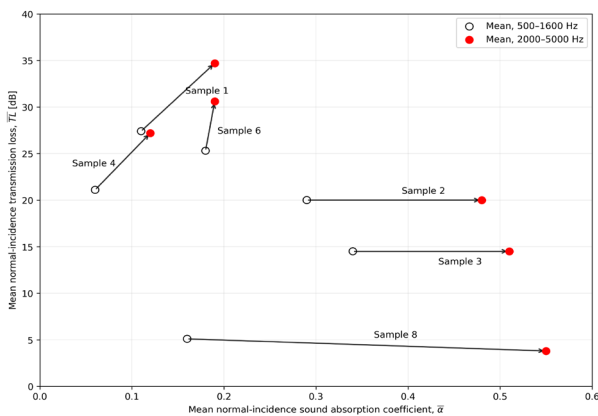


Fig. 4 Frequency-dependent shift in the joint sound absorption–transmission loss performance of the tested materials

No attempt was made to define a universal “balanced” region in the map. Such a boundary would require application-specific weighting of absorption and transmission reduction and could change with the noise spectrum, available installation depth and the role of the material in a multilayer assembly. The graphical approach instead preserves the measured descriptors and allows the reader to identify trade-offs directly. This is particularly useful for early-stage screening, when a designer may wish to retain several candidates with different strengths rather than select one material through a fixed scalar score.

The trajectories separate three broad response patterns. Sample 8 shifts strongly toward higher absorption while remaining a weak transmission-loss element. Samples 1, 4 and 6 move mainly upward, reflecting increasing TL with only modest changes in mean absorption. Samples 2 and 3 shift strongly to the right while their mean TL remains unchanged at the reported precision. Within the open-cell TPE pair, the lower-density Sample 3 is more strongly shifted toward absorption, whereas the higher-density Sample 2 retains the greater TL. The present measurements do not isolate density, pore structure or manufacturing parameters as independent variables, so these differences should be interpreted comparatively rather than causally.

Quantitatively, Sample 8 moves from (0.16, 5.1 dB) to (0.55, 3.8 dB), the strongest rightward displacement in the set. Sample 1 moves from (0.11, 27.4 dB) to (0.19, 34.7 dB), illustrating a predominantly upward shift. Samples 2 and 3 move from (0.29, 20.0 dB) to (0.48, 20.0 dB) and from (0.34, 14.5 dB) to (0.51, 14.5 dB), respectively. The map therefore shows not only which materials occupy different regions of the SAC–TL space but also how their relative positions change with frequency.

From an application perspective, Samples 1, 4 and 6 are more strongly oriented toward transmission reduction, Sample 8 toward absorption, and Samples 2 and 3 provide an intermediate balance. The map therefore extends the earlier qualitative characterisation [9] by quantifying both the position of each specimen and its change with frequency. It also illustrates why ranking materials using only SAC or only TL can be misleading when both acoustic functions are relevant.

The NBR pair also deserves attention. Samples 1 and 6 had similar bulk densities but different reported surface conditions, with Sample 1 having a ground front surface and Sample 6 a non-ground front surface. Their responses were not identical, but the measurements do not permit the differences to be attributed solely to surface treatment because the TL specimen thicknesses also differed and other structural parameters were not independently controlled. Likewise, the low absorption of the closed-cell TPE Sample 4 is consistent with limited penetration of the acoustic field into the internal structure, but cell morphology was not isolated as an independent variable.

The opposite behaviour of Samples 1 and 8 is particularly relevant for multilayer design. The fibrous flax/polypropylene material may be useful as an absorptive layer where reflected energy should be reduced, but its low TL makes it unsuitable as a stand-alone barrier. Conversely, the stronger TL of the cellular NBR specimen is accompanied by relatively weak absorption. Combining materials with complementary functions may therefore be more promising than seeking a single specimen that maximises both descriptors over the entire frequency range.

The open-cell TPE pair provides a different design option. Sample 3 offers the higher mean absorption in both selected intervals, while Sample 2 provides a clear TL advantage. Their higher-frequency mean SAC values are relatively close (0.51 and 0.48), but the corresponding mean TL differs by 5.5 dB. This makes Sample 2 the more balanced of the two when both acoustic functions are required. The comparison also demonstrates why density

alone should not be used as a predictive design parameter: density changes together with pore geometry and processing history, and the present dataset does not contain independent measurements of airflow resistivity, porosity or tortuosity.

For Samples 1, 4 and 6, the higher-frequency interval produces a clear upward displacement in the performance map. Sample 4 increases in both mean SAC and TL, but remains a weak absorber. Sample 6 shows almost no change in mean SAC while its mean TL increases by more than 5 dB. Sample 1 combines the largest high-frequency mean TL with a modest increase in absorption. These differences are useful for screening because they distinguish materials that might appear similar if only one acoustic descriptor or one frequency band were considered.

The two-interval representation is intentionally simple. It does not replace the full one-third-octave spectra shown in Figs. 2 and 3, and it should not be interpreted as a standard rating procedure. Its purpose is to condense the measured data sufficiently to visualise the trade-off between two physically distinct acoustic functions. For engineering selection, the relevant frequency region should ultimately be chosen according to the spectrum of the noise source and the role of the material within the complete acoustic system.

3.3. Interpretation and limitations

The performance map should be interpreted together with the material descriptions in Table 1. Open-cell and fibrous structures allow acoustic energy to enter the material and can promote viscous and thermal dissipation, whereas closed or less permeable structures can restrict penetration. At the same time, transmission loss depends on additional mechanisms and cannot be inferred directly from absorption. The results obtained here illustrate this distinction experimentally: the material with the highest high-frequency absorption has the lowest TL, while the specimen with the highest TL remains a relatively weak absorber.

The selected interval means also reveal that frequency changes the apparent compromise between the two functions. A material that appears favourable in the 500 – 1600 Hz region may occupy a different relative position in the 2000 – 5000 Hz region. This is particularly evident for the fibrous specimen and the open-cell TPE specimens. Consequently, material screening should be linked to the frequency content of the intended application rather than to a single overall ranking.

The interpretation is subject to several limitations. Only one specimen of each material was evaluated, airflow resistivity was not available. In addition, impedance-tube measurements characterise small specimens under normal-incidence conditions and should not be interpreted directly as diffuse-field absorption or full-scale partition sound insulation. The results are therefore most appropriate for comparative material screening and for guiding further development of multilayer acoustic systems.

Several limitations should be considered when interpreting these results. The lack of repeated independent specimens and expanded measurement uncertainty estimates are particularly important when interpreting small numerical differences. The interval means in Table 2

are therefore reported as descriptive values, not as statistically distinct material properties. These limitations do not invalidate the observed broad response patterns, but they constrain the strength of causal conclusions that can be drawn from them.

4. CONCLUSION

A joint frequency-dependent assessment of normal-incidence sound absorption and transmission loss was performed for six polymeric, cellular and fibrous materials. Arithmetic means over 500 – 1600 Hz and 2000 – 5000 Hz, represented in a two-dimensional SAC-TL map, revealed markedly different performance trajectories. Samples 1, 4 and 6 were predominantly transmission-loss-oriented; Sample 8 was strongly absorption-oriented; and Samples 2 and 3 occupied an intermediate region. At 5000 Hz, Sample 8 reached $\alpha = 0.84$ but only 4.3 dB TL, whereas Sample 1 reached 37.6 dB TL with $\alpha = 0.23$. The joint representation preserves the physical distinction between absorption and transmission loss while providing a compact basis for material screening. Further work should include repeated measurements on independent specimens, quantified measurement uncertainty, characterisation of additional porous-material parameters such as airflow resistivity and porosity/open-cell content, and evaluation of optimised multilayer configurations combining complementary acoustic functions.

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TEMPORAL AND PHASE-RESOLVED ASSESSMENT OF TOTAL HEAT RELEASE AND SPECIFIC MASS LOSS OF ACOUSTIC MATERIALS

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Abstract. *Acoustic materials are primarily developed to improve sound absorption and noise control, while their response to thermal exposure is often considered to a lesser extent. This study evaluated the temporal and phase-resolved behaviour of eleven acoustic materials through total heat release (THR), specific mass loss (SML), and flaming duration. The specimens were tested using a mass loss calorimeter at an external heat flux of 50 kW/m². The experimental records were divided into pre-ignition, flaming, and post-flaming periods. Marked differences were observed in the amount, duration, and temporal development of heat release. Sample S1 exhibited the highest THR_{total} and SML_{total}, reaching approximately 121.5 MJ/m² and 5.97 kg/m², respectively, whereas S7 showed the lowest values. Flaming duration alone did not explain the cumulative thermal contribution, since materials with similar durations exhibited substantially different THR values. Visible flaming accounted for most of the heat release and mass loss in the majority of samples. However, S3 showed the most pronounced post-flaming response, with approximately 14 % of THR_{total} and 6.2% of SML_{total} occurring after flame extinction. The results demonstrate that THR, SML, flaming duration, and their temporal distribution should be considered jointly when comparing the fire-response characteristics of acoustic materials.*

Key words: *Acoustic materials, Total heat release, Specific mass loss, Mass loss calorimeter, Fire-response characteristics*

1. INTRODUCTION

Noise pollution represents an important environmental and public health concern, particularly in densely populated urban areas, transportation systems, workplaces, and enclosed spaces with prolonged human occupancy [1,2]. Acoustic materials are widely used to improve indoor and environmental sound conditions by absorbing sound energy, controlling noise transmission, and reducing reverberation [3]. Their main application areas include buildings, transportation systems, and industrial environments, where they may be positioned near the sound source, along the transmission path, or close to the receiver [4]. Sound absorption in these materials is commonly associated with viscous and thermal losses that occur during the interaction of sound waves with the air contained within their structure [5]. Porous, fibrous, foam,

and granular materials are particularly relevant because their interconnected pores and large internal surface areas promote the dissipation of acoustic energy. Their performance depends on factors such as porosity, airflow resistance, thickness, density, pore connectivity, and fibre or particle arrangement [6].

The development of acoustic materials is increasingly directed towards lightweight, multifunctional, and environmentally sustainable solutions [7]. Conventional synthetic materials are therefore being supplemented or replaced by natural fibres, wood-based composites, recycled constituents, and bio-based materials [7,8]. Multilayer structures, graded materials, and composite systems are also being developed to improve sound absorption over wider frequency ranges while retaining acceptable mechanical and physical properties [6]. Consequently, modern acoustic-material design requires a balance between acoustic efficiency, low mass, structural functionality, durability, and environmental sustainability [9].

Structural characteristics that favour sound absorption may also influence material behaviour during thermal exposure. Porosity, density, pore morphology, surface-to-mass ratio, and material thickness can affect heat transfer, oxygen transport, volatile generation, and material consumption. Their influence is not uniform, since the actual fire response also depends on chemical composition, binders, coatings, fillers, inorganic constituents, and flame-retardant additives. Consequently, acoustically similar materials may exhibit substantially different ignition, heat-release, mass-loss, and flame-propagation behaviour [10,11]. However, acoustic materials are primarily designed according to their sound-absorption, mechanical, environmental, and installation requirements, whereas fire behaviour may not always represent the principal design criterion. Existing studies frequently focus on acoustic efficiency, mechanical performance, durability, and sustainability, while comparative information on heat release, mass loss, and fire-effluent generation remains more limited. The interpretation of fire behaviour is further complicated when detailed material formulations are not disclosed.

The response of a combustible solid to thermal exposure is governed by coupled physical and chemical processes. External heating increases the material temperature and may initiate thermal degradation, resulting in the formation of volatile products that can mix and react with oxygen. In polymer-containing materials, the rate and nature of volatile generation depend on molecular structure, cross-linking, crystallinity, additives, fillers, and exposure conditions. These properties may also influence thermal stability, combustible-vapour production, and the formation of a protective or non-combustible residue [10-14]. Therefore, differences in material formulation can lead to substantially different combustion responses even when the materials have been developed for the same acoustic application.

Fire hazards associated with combustible materials include both thermal and non-thermal effects. Thermal hazards are related primarily to the rate and total amount of heat released, whereas non-thermal hazards arise from smoke and toxic, corrosive, or otherwise harmful fire effluents. Small-scale calorimetric testing provides a controlled means of determining selected fire-response characteristics and comparing materials under defined exposure conditions [11].

Heat release rate is one of the principal quantities used to describe the thermal development of a fire. Its integration over time gives the total heat release, which represents the cumulative thermal contribution of the tested specimen during the selected experimental period. Mass loss provides complementary information on the amount of material consumed, volatilised, or otherwise removed during exposure. Mass loss rate quantifies the rate at which specimen mass decreases and may serve as an indicator of material consumption and volatile release [15].

Heat release and mass loss are physically related, since the heat release rate depends on the mass loss rate and the effective heat of combustion of the released products. However, this relationship is not necessarily proportional among different materials. The amount of heat released per unit mass lost may be influenced by the composition and combustion efficiency of volatile products, moisture and non-combustible components, and the formation of residual material [11,15]. Consequently, materials with similar mass losses may release substantially different amounts of heat, and neither heat release nor mass loss alone provides a complete description of their thermal response.

The temporal distribution of heat release and mass loss is also important. Comparisons based solely on cumulative values may conceal differences between materials that release similar total amounts of heat over substantially different durations. Similarly, the disappearance of visible flaming does not necessarily indicate that all thermal processes and mass loss have ceased. Continued processes within the remaining material may result in additional mass loss and, in some cases, a measurable increase in cumulative heat release. Dividing the experimental record into pre-ignition, flaming, and post-flaming periods can therefore provide additional information on when the principal heat release and material consumption occur.

A detailed interpretation of these processes requires information on material composition and formulation. Elemental composition, polymeric structure, organic and

inorganic fractions, binders, fillers, coatings, and flame-retardant additives may influence ignition, volatile generation, heat release, residue formation, smoke production, and fire-effluent composition. When such information is unavailable, heat-release and mass-loss measurements can be used to compare selected fire-response characteristics under specified test conditions. However, they cannot independently identify the mechanisms responsible for the observed behaviour or fully characterise the potential toxic, health, and environmental consequences of combustion.

In this context, the aim of this study was to evaluate the cumulative thermal contribution of selected acoustic materials by analysing the distribution of total heat release and specific mass loss across distinct periods of the fire test. Particular attention was given to the flaming period and the period following flame extinction in order to determine how much heat was released and how much mass was lost during and after visible flaming. The study also examined whether materials with longer flaming durations released greater amounts of heat and whether the post-flaming period made a measurable contribution to the overall thermal response.

2. MATERIALS AND METHODS

2.1. Analysed samples

A total of eleven acoustic material samples developed and/or supplied within the framework of the NATO Science for Peace and Security Programme project SPS MYP G6006, “*Acoustic Multi-Functional Composites for Environmental Risks and Health Hazards Reduction*,” were included in the present study. For consistency in data presentation, the samples were coded consecutively as S1–S11. These designations are used solely for sample identification throughout the study.

Detailed information regarding the material formulations, elemental composition, and basic physicochemical properties was not available to the authors. Consequently, the samples were treated as acoustic materials of unspecified composition, and no attempt was made to establish relationships between their chemical composition and experimentally observed behaviour.

The comparative assessment was therefore based on directly measured quantities obtained during fire testing, including cumulative total heat release, specimen mass, time to sustained ignition, and flame-extinction time. These data were subsequently used to quantify total heat release and specific mass loss during the flaming stage, after flame extinction, and over the entire experimental period.

2.2. Experimental setup and testing procedure

Fire tests were conducted using a custom-built experimental installation located at the Fire Protection Laboratory of the Faculty of Occupational Safety, University of Niš, Serbia. A detailed description of the installation, its operating principle, and calibration procedure was previously provided by Protić et al. [16]. The present experiments were performed using the mass

loss calorimeter (Fire Testing Technology, UK), which enabled the continuous recording of specimen mass and cumulative heat release during thermal exposure. The cited installation uses a conical heater and a real-time mass-measurement system for determining the thermal and mass-loss response of tested materials.

Prior to testing, all materials were cut into specimens measuring 100×100 mm. Each specimen was positioned horizontally in a standard sample holder and secured using a retainer frame to limit deformation and displacement during thermal exposure. Owing to the area covered by the retainer frame, the effective specimen surface exposed to the external heat flux was 8840 mm^2 (0.00884 m^2). The sides and bottom of the specimens were wrapped in aluminium foil, while ceramic-fibre insulation was placed beneath the specimen to adjust its position and reduce heat transfer through the unexposed surfaces. The exposed surface was centred beneath the conical heater, and the distance between the lower edge of the heater and the specimen surface was maintained at 25 mm.

The specimens were exposed to a constant external heat flux of 50 kW/m^2 . Before testing, the conical heater was calibrated for the selected irradiance using a water-cooled Schmidt-Boelter heat-flux meter. During each experiment, specimen mass and cumulative total heat release were recorded continuously as functions of time. Piloted ignition was provided by a spark igniter positioned approximately 13 mm above the centre of the exposed specimen surface.

2.3. Data processing and phase-resolved analysis

The recorded time series were divided into three experimentally defined periods. The pre-ignition period extended from the beginning of thermal exposure to the onset of sustained visible flaming. The flaming period extended from sustained ignition to the disappearance of visible flaming, while the post-flaming period covered the interval from flame extinction to the end of the experiment. Flaming duration was calculated as the difference between the time of flame extinction and the time to sustained ignition, whereas post-flaming duration was calculated as the difference between the end of the experiment and the time of flame extinction.

Total heat release and specific mass loss were determined separately for each period and for the complete duration of the experiment. Phase-specific THR values were obtained from the differences between the cumulative THR values recorded at the corresponding period boundaries. Specific mass loss was calculated from the change in specimen mass during each period and normalised by the effective exposed area defined by the retainer-frame opening. The relative contribution of each period was expressed as a percentage of the corresponding total THR or SML value. Minor negative mass differences resulting from balance fluctuations were treated as zero.

For both parameters, the subscripts pre, flame, and post denote the pre-ignition, flaming, and post-flaming periods, respectively, whereas the subscript total refers to the complete experimental period.

3. RESULTS

The experimental results are presented in three complementary parts. First, the characteristic times and durations of the experimentally defined periods are presented to establish the temporal framework of the tests. Second, the temporal evolution of cumulative total heat release is examined over the complete duration of the experiments to provide an overall comparison of the thermal response of the investigated acoustic materials. Finally, total heat release and specific mass loss are compared across the pre-ignition, flaming, and post-flaming periods and over the complete duration of the experiments.

3.1. Characteristic times and durations of the experimentally defined periods

The characteristic times and durations of the experimentally defined periods are presented in Table 1. Time to sustained ignition ranged from 1 to 12 s, showing that all investigated materials ignited within the first 12 s of exposure to an external heat flux of 50 kW/m^2 .

Table 1 Characteristic times and durations of the experimentally defined periods

Sample	TTI [s]	Flame-out time [s]	Flaming duration [s]	EOT [s]	Post-flaming duration [s]
S1	10	931	921	976	45
S2	12	411	399	427	16
S3	12	411	399	618	207
S4	6	447	441	456	9
S5	3	561	558	587	26
S6	1	469	468	469	0
S7	1	353	352	361	8
S8	2	514	512	541	27
S9	2	494	492	502	8
S10	1	164	163	182	18
S11	3	203	200	204	1

*TTI – time to sustained ignition; EOT – end of test.

Sample S1 exhibited by far the longest flaming period, lasting 921 s. This was followed by S5, S8, S9, S6, and S4, with flaming durations of 558, 512, 492, 468, and 441 s, respectively. Samples S2 and S3 exhibited identical ignition and flame-extinction times, resulting in equal flaming durations of 399 s. Shorter flaming periods were recorded for S7, S11, and S10, amounting to 352, 200, and 163 s, respectively.

The duration of the post-flaming period differed considerably among the samples. Sample S3 exhibited the longest post-flaming period, lasting 207 s, although its flaming duration was identical to that of S2. The post-flaming period of S1 lasted 45 s, while the corresponding values for the remaining samples did not exceed 27 s. For S6, the end of the experiment coincided with flame extinction, and consequently no separate post-flaming period was available. These temporal differences provide the basis for the subsequent comparison of the cumulative and phase-resolved heat release and mass loss results.

3.2. Temporal evolution of total heat release

Figure 1 presents the temporal evolution of cumulative total heat release (THR) for the investigated acoustic materials over the complete duration of each experiment. To improve readability, the results were divided into two panels. Samples S1–S6 are shown in Fig. 1a, while samples S7–S11 are presented in Fig. 1b. Considerable differences were observed among the THR curves in terms of their rate of increase, duration, overall shape, and the total amount of heat released during the experiments.

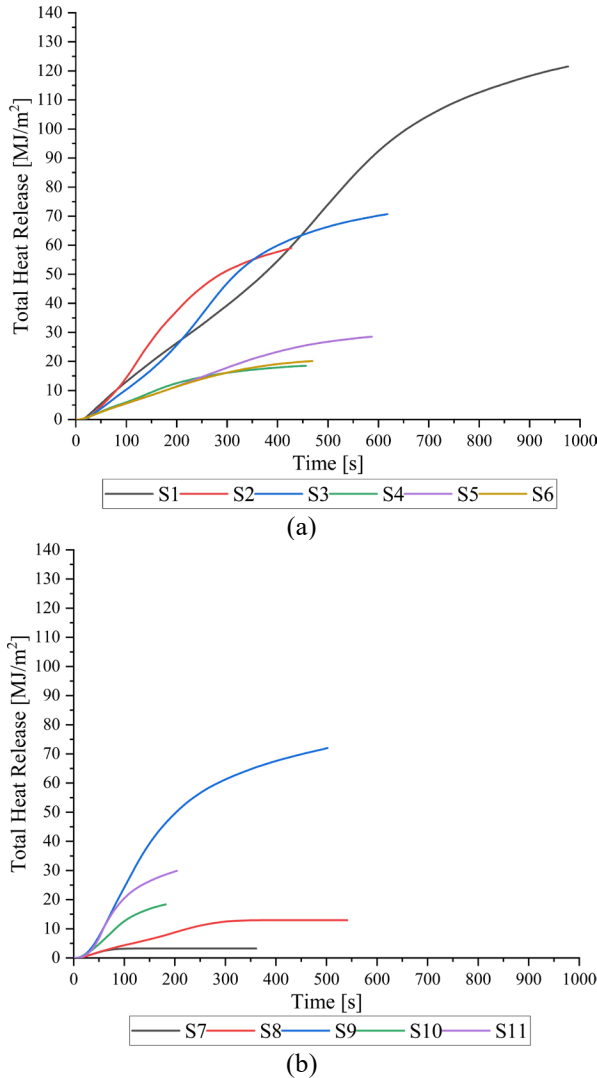


Fig. 1 Temporal evolution of cumulative total heat release over the complete experimental period for the investigated acoustic materials: (a) samples S1–S6 and (b) samples S7–S11

Sample S1 exhibited the longest period of continued increase in cumulative THR and released the greatest amount of heat over the entire experiment, approximately 121.5 MJ/m². Samples S9 and S3 released approximately 72 and 70.7 MJ/m², respectively. Although these values were similar, their temporal profiles differed considerably. Sample S9 showed a steeper increase in cumulative THR and approached an approximately constant value earlier. In contrast, sample S3 exhibited a more gradual accumulation of released heat over a longer experimental period. Sample S2 released approximately 59 MJ/m² during the experiment.

The remaining samples released considerably smaller amounts of heat. Samples S5 and S11 released approximately 28.5 and 29.9 MJ/m², respectively. Despite the similarity of these values, their temporal behaviour differed markedly. The cumulative THR curve of S11 increased over a substantially shorter period, whereas S5 showed a slower and more prolonged accumulation of released heat. Samples S4, S6, and S10 released comparable amounts of heat, ranging from approximately 18.4 to 20.1 MJ/m². Nevertheless, differences were observed in the duration and overall shape of their THR curves. The smallest amounts of heat were released by S8 and S7, with THR values of approximately 12.9 and 3.2 MJ/m², respectively. The cumulative THR curve of S7 approached an approximately constant value relatively early, after which almost no further increase was recorded.

Overall, similar amounts of heat released over the entire experiment did not necessarily correspond to similar temporal profiles. Some materials exhibited a rapid accumulation of released heat over a relatively short period, while others showed a slower and more prolonged increase in cumulative THR. Therefore, the complete THR curves provide information on the temporal development of heat release that cannot be obtained solely by comparing the total amounts of heat released during the experiments.

3.3. Phase-resolved total heat release

The THR values determined for the pre-ignition, flaming, and post-flaming periods, together with the total heat released over the complete duration of each experiment, are presented in Fig. 2. The phase-resolved results revealed pronounced differences among the investigated materials, particularly in the amounts of heat released during and after visible flaming.

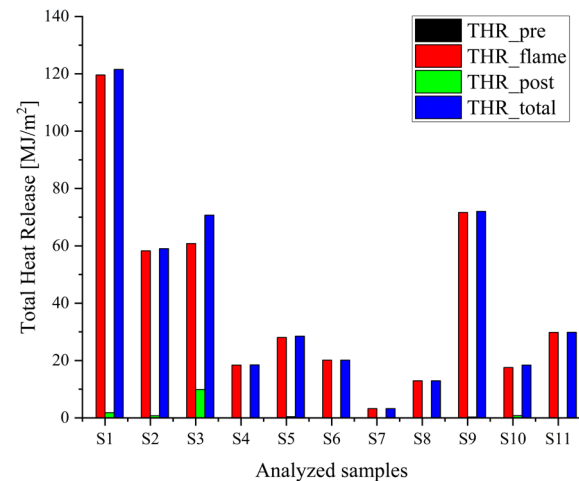


Fig. 2 Total heat release for the investigated acoustic materials during the pre-ignition, flaming, and post-flaming periods and over the complete duration of the experiment

The heat released before ignition was negligible for all investigated samples. The highest THR_{pre} was recorded for S1 and amounted to only 0.085 MJ/m². The corresponding values for the other samples were below 0.01 MJ/m² or equal to zero. Therefore, the pre-ignition period made a negligible contribution to the total heat released during the experiments.

The largest proportion of heat was released during visible flaming. Sample S1 exhibited the highest THR_{flame} , reaching approximately 119.63 MJ/m². Considerably lower values were recorded for S9, S3, and S2, which released approximately 71.67, 60.83, and 58.26 MJ/m², respectively, during the flaming period. Intermediate values were obtained for S11 and S5, with THR_{flame} values of approximately 29.82 and 28.09 MJ/m², respectively. Samples S4, S6, and S10 released between approximately 17.60 and 20.14 MJ/m² during visible flaming. The lowest values were recorded for S8 and S7 and amounted to approximately 12.94 and 3.24 MJ/m², respectively.

The contribution following flame extinction was substantially smaller for most materials. Sample S3 exhibited the highest THR_{post} , amounting to approximately 9.90 MJ/m², followed by S1 with approximately 1.82 MJ/m². Measurable post-flaming contributions were also observed for S10, S2, S5, and S9, with THR_{post} values of approximately 0.80, 0.75, 0.43, and 0.33 MJ/m², respectively. Only minor increases, below 0.10 MJ/m², were recorded for S4 and S11. No additional increase in cumulative THR was recorded for S7 and S8 after flame extinction. For S6, no separate THR_{post} value was available because the end of the experiment coincided with flame extinction.

Comparison of the absolute and relative post-flaming contributions revealed additional differences among the materials. Although S1 exhibited the second-highest absolute THR_{post} , this value represented only approximately 1.5 % of its THR_{total} because of the considerably greater amount of heat released during flaming. In contrast, the lower absolute THR_{post} recorded for S10 accounted for approximately 4.4% of its THR_{total} . Sample S3 exhibited both the highest absolute and the highest relative post-flaming contribution, with approximately 14% of its THR_{total} released after flame extinction. Among the ten samples with a separately defined post-flaming period, visible flaming accounted for more than 98% of THR_{total} in eight samples. Consequently, the THR_{total} values generally followed the same order as the corresponding THR_{flame} values.

3.4. Phase-resolved specific mass loss

The SML values determined for the pre-ignition, flaming, and post-flaming periods, together with the specific mass loss over the complete duration of each experiment, are presented in Fig. 3. Considerable differences were observed among the investigated materials in both the amount and the phase distribution of mass loss.

The specific mass loss before ignition was low for all investigated samples. The highest SML_{pre} values were recorded for S4, S10, and S9 and amounted to approximately 0.061, 0.056, and 0.050 kg/m², respectively. For the remaining samples, SML_{pre} was below 0.035 kg/m². These results indicate that only a small proportion of the total specimen mass loss occurred before the onset of visible flaming.

The greatest mass loss occurred during visible flaming for all investigated samples. Sample S1 exhibited the highest SML_{flame} , amounting to approximately 5.90 kg/m². The next highest values were recorded for S9 and S3, with approximately 4.21 and 4.02 kg/m², respectively. Samples

S2 and S5 exhibited SML_{flame} values of approximately 3.40 and 3.05 kg/m². Intermediate values were obtained for S6, S8, and S11 and ranged from approximately 2.09 to 2.47 kg/m². Lower values were recorded for S4 and S10, amounting to approximately 1.75 and 1.24 kg/m², respectively, while S7 exhibited the lowest SML_{flame} , approximately 0.89 kg/m².

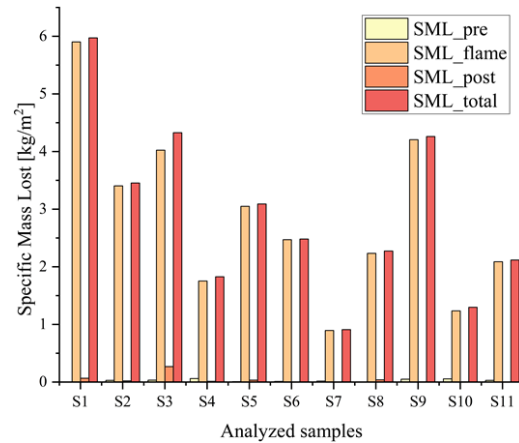


Fig. 3 Specific mass loss of the investigated acoustic materials during the pre-ignition, flaming, and post-flaming periods and over the complete duration of the experiment

Mass loss after flame extinction was considerably smaller than that recorded during visible flaming. Sample S3 exhibited the highest SML_{post} , amounting to approximately 0.269 kg/m². Substantially lower values were recorded for S1, S8, S5, and S2, with SML_{post} values of approximately 0.067, 0.039, 0.033, and 0.021 kg/m², respectively. Post-flaming values below 0.015 kg/m² were obtained for S4, S9, S10, and S11. No measurable mass loss was recorded for S7 after flame extinction. No separate SML_{post} value was available for S6 because the end of the experiment coincided with flame extinction.

When expressed relative to SML_{total} , the flaming period accounted for more than 98 % of the total specific mass loss for S1, S2, S5, S6, S7, S8, S9, and S11. Sample S3 exhibited the largest relative post-flaming contribution, with approximately 6.2% of its SML_{total} occurring after flame extinction. The corresponding contribution for S8 amounted to approximately 1.7 %, while values of approximately 1.1 % were recorded for S1 and S5. For the remaining samples with a separately defined post-flaming period, less than 1 % of SML_{total} occurred after flame extinction. The comparatively lower flaming contributions recorded for S4 and S10, approximately 96 % and 95.3 %, respectively, were associated primarily with their greater pre-ignition mass losses rather than with extensive mass loss after flame extinction.

The SML_{total} values generally followed the same order as the corresponding SML_{flame} values. Sample S1 exhibited the highest SML_{total} , approximately 5.97 kg/m², followed by S3 and S9, with approximately 4.33 and 4.26 kg/m², respectively. Although S9 lost more mass than S3 during the flaming period, the greater post-flaming mass loss of S3 resulted in a slightly higher SML_{total} . Sample S7 exhibited the lowest total specific mass loss, approximately 0.91 kg/m².

4. DISCUSSION

Comparison of the characteristic times and total heat release values showed that flaming duration alone was not sufficient to explain the cumulative thermal contribution of the investigated materials. Sample S1 exhibited both the longest flaming period and the highest THR_{total} . However, this relationship was not consistently observed for the remaining samples. Samples S5 and S8 exhibited relatively long flaming periods but released considerably less heat than S3 and S9. Conversely, S11 reached a THR_{total} of approximately 29.9 MJ/m² despite a substantially shorter flaming period. These differences indicate that total heat release depends not only on the duration of visible flaming but also on the temporal development of heat release during that period.

A general correspondence was observed between total heat release and specific mass loss. Sample S1 exhibited the highest values of both THR_{total} and SML_{total} , while S3 and S9 were also among the materials with the greatest heat release and mass loss. Sample S7 exhibited the lowest values of both parameters. Nevertheless, the relationship between THR and SML was not directly proportional. For example, S8 exhibited a slightly higher SML_{total} than S11, whereas its THR_{total} was less than half the value recorded for S11. Similarly, S6 lost substantially more mass than S10, although their total heat release values were comparable.

This lack of direct proportionality is consistent with the relationship between mass loss and heat release described in calorimetric studies. The thermal contribution associated with a given amount of mass loss depends on the effective heat of combustion and combustion efficiency of the released products, as well as on moisture-related mass loss, non-combustible constituents, and residue formation [11,15]. The differences observed among the investigated samples may therefore reflect variations in their combustible fraction, the chemical nature of the volatile products, and the amount and properties of the residue formed during exposure [10,11]. However, detailed information on the composition and structure of the investigated materials was not available. The mechanisms responsible for the observed differences between THR and SML therefore cannot be established from the present results, and the interpretation must remain limited to the experimentally measured thermal and mass-loss responses.

Among the samples for which a separate post-flaming period was available, the greatest recorded heat release and mass loss generally occurred while visible flaming was present. Sample S3 represented the clearest deviation from this pattern. After flame extinction, this material released approximately 14 % of its THR_{total} and lost approximately 6.2 % of its SML_{total} . It also exhibited the longest post-flaming period, lasting 207 s. The larger post-flaming contributions of S3 were therefore accompanied by a prolonged post-flaming response. However, the present phase-resolved data do not allow the separate effects of post-flaming duration and the intensity of the continued processes to be determined.

The relative post-flaming contributions to THR and SML were not proportional in all samples. For S3, the relative post-flaming contribution to THR was more than twice the corresponding contribution to SML. Sample S10

also exhibited a post-flaming THR contribution of approximately 4.4 %, although only a very small proportion of its total mass loss occurred after flame extinction. In contrast, S8 exhibited a small but measurable post-flaming mass loss without an additional increase in cumulative THR. These results indicate that continued mass loss after flame extinction does not necessarily produce a proportional increase in heat release. Although the recorded responses indicate that measurable changes continued after the disappearance of visible flames, the processes responsible for these changes cannot be identified without compositional and residue analyses.

The combined evaluation of THR, SML, and their temporal distribution therefore provides a more complete description of material behaviour than any of these quantities considered independently. Flaming duration characterises the persistence of visible combustion but does not account for differences in the temporal development of heat release. Specific mass loss quantifies material consumption but does not directly indicate the corresponding thermal contribution. Furthermore, total values alone may conceal heat release or mass loss occurring after flame extinction. The phase-resolved approach applied in this study enabled these differences to be identified. Post-flaming contributions to THR and SML were small for most materials, whereas the most pronounced post-flaming response was recorded for S3. Less extensive deviations were observed for S10 in terms of heat release and for S8 in terms of mass loss.

5. CONCLUSION

This study evaluated the thermal response of eleven materials intended for improving acoustic performance by analysing the temporal evolution and phase distribution of total heat release and specific mass loss. The investigated samples exhibited substantial differences in the amount, duration, and temporal development of heat release. Sample S1 showed the highest THR_{total} and SML_{total} , whereas S7 exhibited the lowest values of both parameters. Materials with similar total heat release did not necessarily exhibit similar temporal profiles, demonstrating that the total amount of heat released alone does not fully describe their behaviour during thermal exposure.

Visible flaming accounted for the predominant proportion of both heat release and mass loss for most of the investigated materials. Nevertheless, the phase-resolved analysis identified differences that were not evident from the total values alone. Sample S3 exhibited the most pronounced post-flaming response, with approximately 14 % of its THR_{total} and 6.2% of its SML_{total} occurring after flame extinction. A smaller but still notable post-flaming contribution to heat release was recorded for S10. These findings show that the disappearance of visible flaming did not necessarily coincide with the complete cessation of measurable heat release and mass loss for all tested materials.

A general correspondence was observed between total heat release and specific mass loss, since materials with greater mass loss commonly released larger amounts of heat. However, this relationship was not directly proportional. Certain samples with comparable mass loss

exhibited considerably different heat release, while materials with similar total heat release showed different temporal profiles and flaming durations. Consequently, flaming duration, total heat release, specific mass loss, and their temporal distributions should be considered together when assessing the thermal response of acoustic materials, since none of these quantities alone provides a complete description of their behaviour.

The significance of the present analysis extends beyond the simple determination and comparison of individual THR and SML values. By resolving the experimental response into pre-ignition, flaming, and post-flaming periods, the applied approach identifies when the principal thermal contribution and material consumption occur and whether measurable changes continue after the disappearance of visible flaming. This distinction is essential because materials with comparable THR_{total} or SML_{total} values may exhibit markedly different temporal behaviours and therefore cannot be regarded as equivalent from the standpoint of their response to thermal exposure. THR_{total} quantifies the cumulative thermal contribution of a material under the applied test conditions, SML_{total} indicates the overall extent of material consumption, flaming duration characterises the persistence of visible combustion, while the phase-resolved THR and SML values reveal how these contributions are distributed over time. Their combined interpretation therefore provides a physically meaningful framework for the comparative fire-response assessment of acoustic materials, including cases in which detailed compositional information is unavailable. Such an approach can support the preliminary selection and development of acoustic materials, indicate formulations requiring improvement, and identify samples that should be prioritised for more comprehensive chemical, thermal, smoke, and fire-effluent analyses. The contribution of the present study consequently lies not merely in reporting a set of experimentally determined parameters, but in demonstrating how their integrated and time-resolved interpretation can support more informed decisions regarding the development and application of acoustic materials in environments where acoustic performance must be considered together with fire safety.

The findings should be interpreted as selected fire-response characteristics of the tested materials under the applied experimental conditions. They should not be regarded as a complete assessment of their combustion behaviour, fire hazard, or potential harmful effects. The available THR and SML data describe the amount and temporal distribution of released heat and lost mass, but they do not identify the chemical reactions occurring during thermal decomposition, the nature of the remaining residue, or the composition and toxicity of the released fire effluents.

A more detailed interpretation of the observed differences requires additional information on the composition and structure of the investigated materials. Elemental analysis would provide an important initial basis for identifying differences in material composition, but it should be combined with further characterisation of the material formulations, thermal decomposition behaviour, and combustion residues. Future investigations should also include qualitative and quantitative analysis of gaseous and

particulate fire effluents. Such an integrated approach would enable the experimentally observed thermal and mass-loss responses to be related to material composition and would support a more comprehensive assessment of fire safety and potential health and environmental hazards associated with the use of acoustic materials.

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NOISE AND LEARNING: COGNITIVE AND PEDAGOGICAL PERSPECTIVES

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Abstract. Noise is one of the most significant environmental factors affecting cognitive processes and learning efficiency. Research indicates that increased noise levels lead to reduced concentration, greater fatigue, and lower academic achievement. The aim of this paper is to analyze the effects of noise on the learning process through a review of relevant literature and empirical studies. Special attention is given to the psychological and physiological consequences of noise exposure, as well as pedagogical strategies for mitigating its negative effects. Findings suggest that systematic control of the acoustic environment – through architectural, technological, and methodological measures – can substantially improve students' concentration, motivation, and academic performance. It is concluded that integrating noise reduction measures into educational institutions is essential for enhancing the quality of teaching and achieving better learning outcomes.

Key words: Noise, Learning, Concentration, Academic Performance, Acoustic environment

1. INTRODUCTION

In contemporary environments, noise has become one of the most widespread environmental factors directly affecting individuals' psychophysical health and cognitive performance. Although noise has traditionally been viewed in terms of physical hearing damage or disruption of comfort, its impact on complex cognitive processes – particularly learning, memory, and attention – represents one of the key issues in contemporary pedagogy, andragogy, psychology, and the ergonomics of educational spaces [1].

The learning process requires a high level of concentration, efficient functioning of working memory, and the ability of selective attention. However, the presence of acoustic distractors in educational and home environments leads to what is known as cognitive overload. Noise not only directly masks speech and makes verbal communication in the classroom more difficult, but also forces the brain to expend additional cognitive resources filtering out irrelevant sounds instead of processing and acquiring teaching content [2].

In the traditional approach to occupational safety, noise is viewed primarily as a risk to the auditory system, with threshold values defined in relation to permanent hearing damage. Such an approach fails to address the domain in which noise is most expensive to both the individual and

society – the domain of learning. Low- and moderate-intensity noise, well below the thresholds for auditory damage, systematically impairs the processes of attention, working memory, and speech comprehension. These are non-auditory effects that cannot be detected through audiometry, but can be reliably observed in educational achievement. The aim of this paper is to systematize the theoretical frameworks and empirical evidence concerning these effects, interpret them from a pedagogical, andragogical and psychological perspective, and draw implications for improving the current situation in the future.

2. THEORETICAL BACKGROUND

Numerous authors confirm the disruptive effect of irrelevant sound (the *Irrelevant Sound Effect*), particularly speech as background noise, on the learning and recall of verbal material [3,4]. The phonological loop is an “open channel” for speech, meaning that any external verbal signal enters the system and can disrupt memory for the order of information. From a pedagogical perspective, it is important that this effect also occurs when the material is presented visually, that is during reading and silent study, which means that it is not simply a matter of acoustic masking. Cognitive Load Theory [5] enables the didactic operationalization of these findings. Working memory has a strictly limited capacity, while noise represents a source of extraneous cognitive load that consumes resources intended for schema construction. The consequence is not merely slower task completion but structurally poorer knowledge acquisition: less capacity remains for deep processing, integration with prior knowledge, and transfer. The meta-analytic synthesis by Szalma and Hancock [6] shows that the effects of noise are not unambiguous and are best explained by a resource model in which the type of noise, the nature of the task, and individual characteristics jointly moderate the outcome. This finding calls for caution: noise does not affect everyone uniformly but selectively impairs tasks that require verbal working memory and sustained attention.

Alongside cognitive interference, a perceptual mechanism is also involved. Speech intelligibility in the classroom is determined by the signal-to-noise ratio and reverberation time. Because of their incomplete

development, children require a higher signal-to-noise ratio than adults to achieve the same level of intelligibility [1]. Shield and Dockrell [7] report that a decrease in the signal-to-noise ratio of only approximately 2 dB can slow academic progress. Instructional content that is not reliably perceived cannot be cognitively processed either – the acoustics of the classroom thus become a prerequisite for didactic communication.

From a psychophysiological perspective, chronic exposure to noise activates the stress response, accompanied by increased secretion of cortisol and catecholamines, while, through annoyance and sleep disturbance, it can also indirectly affect academic achievement. Evans and Stecker [8] show that uncontrollable environmental stressors produce a pattern of learned helplessness, characterized by reduced persistence and difficulties in learning new tasks. In this way, the effect of noise extends from the cognitive domain into the motivational domain. This is particularly important for educators and adult-education professionals, since noise can undermine learners' willingness to invest effort and their motivation to learn.

The results of empirical research show that exposure to noise significantly impairs reading and memory in children, but also that these effects are reversible when the noise is removed. One of the best-known and most frequently cited studies (the quasi-experimental study conducted around Munich Airport) in the field of environmental psychology and the effects of noise on children's cognitive development [9], provided unusually strong evidence that noise leads to poorer learning outcomes among schoolchildren and demonstrated a causal relationship rather than merely a correlation. A cross-national study by Stansfeld and colleagues [10], involving nearly 3,000 children, demonstrated a linear relationship between aircraft-noise levels and declines in reading and memory, independent of socioeconomic factors. Subsequent analyses estimate that a 5 dB increase corresponds to a reading delay of approximately two months. The study by Klatte et al. [11] confirmed that these effects also occur at lower noise levels, below 60 dB, with a 10-20 dB increase resulting in a reading delay of one to two months. Classic studies by Bronzaft and McCarthy [12,13] showed that children growing up near railway lines could fall behind by as much as one year, but that the difference disappeared after acoustic interventions. Shield and Dockrell [7] documented the negative effects of both external and internal noise on literacy, mathematics, and science, particularly among older children.

Review studies indicate that the acute effects of noise are more pronounced in children than in adults [1], which may be explained by the compensatory role of adults' metacognitive strategies. However, this compensation comes at a cost: it entails additional cognitive load [5] and more rapid fatigue. These findings are important for adult education practice and for the delivery of professional development, lifelong learning, and online learning programs.

In this context, teaching staff in educational institutions must also be considered. In noisy environments, teachers unconsciously increase the intensity, pitch, and duration of phonation (the Lombard effect), which, under prolonged exposure, leads to occupational voice disorders.

Systematic reviews consistently show that teachers are among the occupational groups with the highest prevalence of voice disorders, significantly exceeding that of the general population, with a higher incidence among women. Thus, pedagogical effectiveness is directly linked to teachers' occupational safety and health: improving classroom acoustics is both a didactic measure and a means of protecting the health of employees and teaching staff.

The World Health Organization guidelines [14] set a recommended classroom noise level of 35 dB(A) L_{Aeq} during lessons, with a reverberation time of approximately 0.6 seconds. More recent European guidelines [15] recommend keeping aircraft noise below 45 dB L_{den} . The national regulatory framework was established by the 2010 Regulation on Noise Indicators [16] (Table 1).

Table 1 Recommended and prescribed noise limit values in international and national frameworks

Source/regulation	Space and indicator	dB(A)
WHO (1999) [14]	Classroom, L_{Aeq} (teaching)	35
WHO (2018)	Airplane noise, L_{den}	< 45
ANSI/ASA S12.60	Classroom, background level	35
Regulation RS 75/2010	Classroom/listening room (inside)	40
Regulation RS 75/2010	School zone, day/evening	50
Regulation RS 75/2010	School zone, night	45

A comparison shows that the national threshold for teaching and educational premises, set at 40 dB(A), is less stringent than both the WHO recommendation and the ANSI standard of 35 dB(A) [17]. Given that reading deficits have been documented even at noise levels below 60 dB [11], there is a scientifically grounded argument for reconsidering this value when harmonizing secondary legislation with the 2021 Law on Environmental Noise Protection [18] and Directive 2002/49/EC [19].

3. METHODOLOGY

In contemporary higher education, the learning process does not take place solely through traditional lectures in lecture halls, but also through individual and group work in reading rooms, libraries, and open learning spaces within the university campus. Within these spaces, students are exposed to specific acoustic challenges – from internal noise generated by the students themselves (conversation, movement, and the use of technical devices), through poor room acoustics, to background noise produced by equipment and installations [20]. Although learning at the university level relies on the well-developed self-regulatory cognitive mechanisms of young adults, research shows that internal noise significantly impairs the efficiency of acquiring complex academic content [21].

The complex tasks students encounter on a daily basis, such as analyzing specialized literature, solving mathematical and engineering problems, and preparing for examinations, require maximum working-memory capacity and a high level of concentration. Internal noise, particularly in the form of background speech (the so-called *irrelevant speech effect*), acts as a powerful cognitive distractor [22]. The student's brain automatically processes the phonological structures present in the environment, thereby directly placing a burden on the

capacity of the central executive component of working memory and reducing the ability to comprehend and retain text [1,23].

Building on these and other findings, the present study focuses on students and the impact of noise on students' knowledge acquisition and learning in higher education institutions. The study was conducted with the aim of gaining insight into students' experiences and attitudes regarding the effects of noise on their cognitive and academic performance. More specifically, the study sought to answer the following research questions: (1) how often students are exposed to noise during classes; (2) the extent to which different sources of noise act as distracting factors during classes; (3) how students perceive the impact of noise on their cognitive abilities, the quality of communication with teachers, their motivation to learn, and their active participation in classes; and (4) what attitudes students hold regarding the need to provide "quiet" study rooms at their faculty.

The study was conducted by means of a questionnaire designed specifically for the purposes of the research (the questions and response options are presented in the following section of the paper), which was completed by students both online, via a link, and in paper-and-pencil format. The research sample consisted of 226 students. The largest proportion were first-year students, accounting for slightly more than one-third of the sample (33.2 %), while the smallest proportion consisted of students enrolled in master's or doctoral studies (12.4 %). A slightly higher percentage (14.2 %) comprised fourth-year students, whereas second- and third-year students were represented in nearly identical proportions in the research sample (19.5 % and 20.8 %, respectively). Almost 60 % of the students were female and nearly 40 % were male, while one student selected the response *I prefer not to answer*. The collected data were compiled and analyzed using the SPSS statistical software package, and the results are presented below.

4. RESULTS AND DISCUSSION

4.1. Frequency of exposure to noise during classes

In response to the question, "How often do you encounter noise during classes at your faculty?", almost half of the respondents (48.7 %) stated that such situations were *rare*, while one-third (33.6 %) indicated that they encountered noise during classes *occasionally*. Interestingly, nearly equal percentages of students reported encountering noise during classes *frequently* (7.1 %) or *never* (8%). Only 1.3% of students stated that they *always* encountered noise during classes at the faculty. The same percentage of students (1.3 %) did not answer this question.

4.2. Sources of noise during classes as a distracting factor

Table 2 presents students' views regarding the extent to which they perceive particular sources of noise from the list provided as distracting factors during classes. The noise source proposal is adapted according to [23].

Table 2 Sources of noise during classes as a distracting factor

Noise sources		s1	s2	s3	s4	s5	s6	s7	s8	s9	s10
a1	N	44	83	123	132	148	41	88	31	34	97
	%	19.5	36.7	54.4	58.4	65.5	18.1	38.9	13.7	15.0	42.9
a2	N	60	64	50	37	40	71	54	48	56	36
	%	26.5	28.3	22.1	16.4	17.7	31.4	23.9	21.2	24.8	15.9
a3	N	57	46	32	27	23	55	46	58	51	47
	%	25.2	20.4	14.2	11.9	10.2	24.3	20.4	25.7	22.6	20.8
a4	N	38	21	11	16	3	40	22	54	52	25
	%	16.8	9.3	4.9	7.1	1.3	17.7	9.7	23.9	23.0	11.1
a5	N	23	8	5	9	8	15	9	28	29	17
	%	10.2	3.5	2.2	4.0	3.5	6.6	4.0	12.4	12.8	7.5
a6	N	4	4	5	5	4	4	7	7	4	4
	%	1.8	1.8	2.2	2.2	1.8	1.8	3.1	3.1	1.8	1.8
M		2.77	2.19	1.85	1.88	1.66	2.69	3.09	3.09	2.99	2.30
SD		1.32	1.23	1.19	1.30	1.14	1.24	1.33	1.33	1.33	1.40

Note: s1 = whispering or conversations among classmates; s2 = movement around the classroom (by the teacher or students); s3 = noise coming from equipment (e.g. computer, projector); s4 = the sound of chalk (writing on a board); s5 = noise produced by stationary items (e.g. ballpoint pens); s6 = noise coming from the hallway; s7 = noise from a neighboring classroom; s8 = noise heard "through the window"; s9 = unexpected noise (e.g. slamming doors or windows, waste removal, cleaning, etc.); s10 = use of mobile phones during classes. Answers: a1 = It doesn't distract me at all; a2 = It partially distracts me; a3 = Neutral; a4 = It distracts me; a5 = It distracts me a lot; a6 = No answer.

According to the arithmetic mean values given in Table 2 (M ranging from 1.66 to 3.09), it can be concluded that most sources of noise do not represent a distracting factor for students. Thus, more than half of the students stated that they were *not distracted at all* by noise coming from equipment (e.g. computer, projector) (54.4 %), the sound of chalk (writing on a board) (58.4 %), or noise produced by stationery items (e.g. ballpoint pens) (65.5 %). In addition, approximately 40 % of students stated that they were not distracted at all by movement around the classroom (by the teacher or students) (36.7 %), noise coming from a neighboring classroom (38.9 %), or mobile-phone use (42.9 %).

Regarding the remaining responses, it is noticeable that one-quarter or one-fifth of the students selected either *partially distracts me* or a *neutral* response for the respective source. For example, whispering or conversations among classmates partially distracted 26.5 % of students, while 25.2 % expressed a neutral view. Noise from a neighboring classroom partially distracted 28.3 % of students, while 20.4 % gave a neutral response. Noise heard through the window partially distracted 21.2 % of students, while 25.7 % considered it neutral. Unexpected noise (e.g., slamming doors or windows, waste removal, cleaning, and similar activities) partially distracted 24.8 % of students, while 22.6 % gave a neutral response.

For the last two sources, approximately 20 % of students reported that they were *distracted*. When the response *It distracts me a lot* is considered, it becomes clear that noise can indeed act as a disruptive factor during classes, although this response was selected by only a small number of students. Among the students who selected this response, the highest percentage were most distracted by

unexpected noise (12.8 %), noise heard “through the window” (12.4 %), and whispering or conversations among classmates (10.2 %).

In a study conducted among students aged 16 to 18 [24], sources of noise such as computers, projectors, and other equipment; students or teachers from neighboring classrooms; students outside the classroom (e.g. on a playground); unexpected sounds (e.g. banging on doors, bins clattering); and similar sources were, in most cases, assessed as annoying. In particular, conversations among other students in the classroom and noise produced by students in a neighboring classroom were identified as the sources that most interfered with students’ ability to hear the teacher.

4.3. The impact of noise during classes on students’ cognitive abilities, communication quality, and motivation

Table 3 presents students’ views regarding the impact of noise during classes on their ability to remember and retain information, the quality of communication between teachers and students, their motivation to learn, and their active participation in classes.

Table 3 The impact of noise during classes on students’ cognitive abilities, communication quality, and motivation

Questions		q1	q2	q3
a1	N	18	7	31
	%	8.0	3.1	13.7
a2	N	81	79	57
	%	35.8	35.0	25.2
a3	N	84	53	85
	%	37.2	23.5	37.6
a4	N	34	67	46
	%	15.0	29.6	20.4
a5	N	8	19	5
	%	3.5	8.4	2.2
a6	N	1	1	2
	%	0.4	0.4	0.9
M		2.30	2.72	3.07
SD		1.40	0.97	1.07

Note: q1 = To what extent does noise during class affect your ability to remember and retain information?; q2 = Do you think that noise affects the quality of communication between teachers and students during lectures?; q3 = How does the presence of noise in the classroom affect your motivation for learning and active participation in classes? Answers: a1 = It doesn’t affect it at all; a2 = It affects it to a small extent; a3 = It moderately affects it; a4 = It greatly affects it; a5 = It affects it to a very large extent; a6 = No answer.

According to the data presented in Table 3, most students assessed the impact of noise on their cognitive abilities, communication quality, and motivation as low to moderate (M ranging from 2.30 to 3.07). Nearly the same percentage of students, just over one-third, believed that noise had a *minor effect* on their ability to remember and retain information (35.8 %) and on the quality of communication they established with the teacher during lectures (35 %). Similarly, nearly the same percentage of students believed that noise had a *moderate effect* on their ability to remember and retain information (37.2 %) and on

their motivation to learn and actively participate in classes (37.6 %).

When it comes to an answer *It greatly affects it*, almost 30 % of students (29.6 %) believed that noise greatly affected the quality of communication between teachers and students during classes; approximately 20 % believed that noise greatly affected their motivation and active participation in classes; and 15 % believed that noise greatly affected their ability to remember and retain information. When the percentage of students who selected the response *It affects it to a very large extent* is added, the data show that approximately one-fifth of students had experienced the effects of noise on their memory and retention of information, as well as on their motivation to learn and actively participate in classes. In addition, slightly less than half of the students believed that noise affected the quality of communication between teachers and students during lectures. Naturally, this effect can be characterized as negative, adverse, and undesirable. On the other hand, one-quarter of the students (25.2 %) assessed the impact of noise on their motivation and activity during classes as *minor*.

The impact of noise on the academic and/or cognitive performance (attention, memory, comprehension, and overall academic performance) of children and adolescents in primary and secondary education was examined by Fretes and Palau [25]. Through a theoretical analysis of 21 studies, the authors concluded that noise has a significant negative impact on academic and cognitive performance, following the principle that as noise levels increase, performance levels decrease. They also found that younger students, particularly those aged 6 to 12, are especially sensitive to noise and perform less effectively in noisy conditions. In this regard, when the age of the respondents is taken into account, the views of most students – that noise has either no effect or only a minor to moderate effect on their academic and cognitive performance, can be better understood.

4.4. Provision of “quiet” study rooms at the faculty

Students’ attitudes toward the need to provide “quiet” study rooms at the faculty were examined through two questions: “Do you believe that your faculty should provide classrooms and study rooms that enable the uninterrupted delivery of classes, with appropriate acoustic insulation and protection from noise?” and “How important would it be for you to have access to rooms with controlled acoustics?”

In response to the first question, more than half of the students (55.8 %) believed that the faculty *should provide* classrooms and study rooms that enable the uninterrupted delivery of classes, with appropriate acoustic insulation and protection from noise, while one-third of the students were *uncertain* (33.2 %). A total of 10.2 % of students selected the response *No*, whereas 0.9 % did not answer the question.

Regarding the second question, concerning the importance of access to quiet rooms, identical percentages of students (31.4 %) stated that having access to rooms with controlled acoustics would matter to them either *moderately* or *greatly*. A total of 15.5 % of students selected the response *A little*, while approximately 10 %

selected either *Not at all* (10.2 %) or *Very much* (9.7 %). Several students (1.8 %) did not answer this question.

The views of the majority of students, who supported the need for such rooms, are consistent with the findings of other studies demonstrating the positive effects of good classroom acoustics on speech intelligibility [26], stress reduction among teaching staff, as indicated by lower heart rates [27], students' concentration and behavior [28], and motivation and the quality of interaction with teachers and other students [29], among other outcomes.

5. CONCLUSION

The results of relevant research converge on a clear conclusion: noise is a factor that systematically impedes learning, and it does so at levels far below those associated with hearing damage. The mechanisms are multiple and complementary – interference with the phonological loop, increased extraneous cognitive load, speech masking, and a stress response with motivational consequences.

Viewed through the lens of higher-education didactics, the impact of noise on students within university spaces manifests across several key dimensions: reduced intelligibility of the lecturer's speech during classes (insufficient sound insulation requires greater mental effort and leads to faster fatigue during instruction); disruption of independent study in reading rooms and shared spaces; increased subjective stress and reduced motivation (the need to ignore ambient auditory stimuli contributes to academic exhaustion).

Although the findings of this study show that most respondents rarely or only occasionally encounter noise during university classes, and that different types of noise are generally not perceived as disruptive, it should not be overlooked that some students frequently encounter noise and find it highly disturbing. The sources identified as highly disruptive in the largest number of cases were unexpected noises (e.g. doors or windows slamming, waste removal/cleaning activities), noise coming “through the window,” and whispering/conversation among classmates during teaching. This result confirms that the design of modern educational spaces and their microclimatic conditions must treat acoustic comfort as a basic prerequisite for effective teaching and learning [20]. Accordingly, research on the impact of noise on the learning process has not only theoretical significance within pedagogical and psychological sciences, but also provides practical guidelines for optimizing teaching and educational work and for the architectural design of schools and universities. Consistent with this, most respondents stated that their faculty needs classrooms and study rooms that enable the uninterrupted conduct of teaching, with appropriate acoustic insulation and protection from noise. Student experiences further indicate that noise greatly and to a very large extent affects their cognitive and academic performance: about one-fifth of students report negative effects of noise on memory and retention of information, as well as on motivation for learning and active participation in class, while slightly less than half believe that noise negatively affects the quality of communication between teachers and students during lectures.

Based on the theoretical and empirical findings, it can be concluded that acoustic treatment of teaching spaces is necessary (e.g. the use of absorptive ceilings, wall coverings, and floor materials designed to achieve a reverberation time not exceeding 0.6 s), along with urban planning that treats school zones as protected areas. Organizational and pedagogical measures are also required, such as optimizing class sizes, appropriately scheduling activities, and using speech amplification systems (these can mitigate the negative effects of noise but cannot replace structural interventions). In the context of distance learning, it is essential to explicitly educate students about the acoustic conditions of their personal learning spaces, since these spaces lie beyond institutional control and have become decisive for the quality of the educational process.

For pedagogical and andragogical theory, this means that the acoustic quality of space should be included among didactic factors, on an equal footing with teaching methods and media. From the perspective of occupational health and safety, the results point to the need to expand the scope of protection from hearing to cognition, and from students to teachers. A quiet learning space is not a comfort – it is a condition for knowledge acquirement. Ensuring optimal acoustic conditions in higher-education institutions is therefore not merely a matter of comfort, but a direct prerequisite for preserving students' cognitive resources and achieving high academic outcomes.

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ENVIRONMENTAL VIBRATION ASSESSMENT CRITERIA FOR TRANSPORT AND CONSTRUCTION SOURCES: A COMPARATIVE REVIEW OF SELECTED EUROPEAN PRACTICES

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Abstract. *Unlike environmental noise, environmental vibration is not governed by a harmonized EU-wide regulatory framework. Environmental vibration from road traffic, railways, metro systems, construction and blasting is regulated through heterogeneous standards, statutory provisions and project criteria. This review compares European approaches for occupants, structures and vibration-sensitive uses, supported by selected international benchmarks. The analysis separates source, propagation path, receptor, descriptor, frequency treatment, exposure rule, measurement position and legal status. Particular attention is given to metro-induced ground-borne vibration and the associated re-radiated ground-borne noise, i.e. audible sound radiated inside buildings by floors, walls and ceilings excited by vibration transmitted through the ground and building structure. The principal descriptors include weighted RMS acceleration, vibration dose value, peak particle velocity, KB indices, v_{max}/v_{per} , the Spanish L_{aw} index, and logarithmic vibration velocity levels. Verified numerical criteria are compared only when they use the same assessment descriptor and a sufficiently comparable measurement context. The results show that national values cannot be reliably ranked or converted unless their measurement and decision contexts are aligned. A minimum reporting matrix is proposed to support transparent cross-country comparison and future European guidance.*

Key words: *Environmental vibration, Ground-borne vibration, Railway and metro, Construction vibration, Human response, Building damage*

1. INTRODUCTION

Environmental vibration is generated by heavy road vehicles, surface and underground railways, tramways, piling, compaction, demolition, tunnelling and blasting. It may be perceived through floors, walls or furniture. Vibrating building elements may radiate ground-borne noise and substantially higher amplitudes may cause cosmetic or structural damage [1–7]. These outcomes involve different response mechanisms and assessment criteria.

European practice is less harmonized than environmental-noise regulation and combines legally binding values, national standards, administrative guidance and project-specific requirements [2–4,8–20]. Human-

response criteria commonly use weighted acceleration or velocity, RMS, VDV or standard-specific indices, whereas structural criteria generally use PPV with frequency and building classifications [2–6,8,17–19,21]. Sensitive equipment is normally assessed spectrally [5].

Metro systems require separate attention because vibration propagates through the track, tunnel, ground, foundations and receiving structure, where it can produce both perceptible motion and re-radiated low-frequency sound [1,5,7,22,23]. Vibration and ground-borne noise must therefore be assessed in parallel.

The review develops a structured framework for comparing European criteria, identifies methodological convergence and divergence, and defines the information needed for transparent reporting. ISO 2631-2:2026 [21] and DIN 4150-2:2025-08 [8] are treated as current editions, while the FTA framework is included as an influential metro benchmark [5].

2. OBJECTIVES AND REVIEW QUESTIONS

The review examines how transport- and construction-induced vibration is formally assessed, how criteria for people, structures and sensitive uses are separated, which descriptors, frequency treatments, exposure periods and measurement positions are applied, when ground-borne noise is assessed, and under which conditions cross-country numerical comparison is defensible. Sections 3–6 establish the analytical basis, Section 7 presents verified criteria and national frameworks, Sections 8–10 compare their implications, and Section 11 states the conclusions.

3. REVIEW METHODOLOGY

Sources were classified into four tiers: legislation and official rules; current ISO and national standards; official transport or environmental manuals; and peer-reviewed studies or technical reports used for interpretation. Official catalogue records verified the title, edition, date and scope of paywalled standards. Numerical values were included

only when confirmed in an authorized text or an official document applying the standard.

The scope covers road, railway, metro, tram, construction, tunnelling, demolition and blasting vibration affecting occupants, buildings and vibration-sensitive uses. Occupational exposure, vehicle occupants, seismic design, machinery monitoring, ships and aircraft are excluded.

A structured narrative search combined source, impact and regulatory terms in English and, where necessary, national languages. Official standards catalogues, legislation portals, government guidance, bibliographic services and technical repositories were searched. The verification was last updated in September 2026.

Documents were eligible when they addressed an included environmental-vibration source and defined a

measurement procedure, numerical criterion or institutional decision rule traceable to an issuing body. Superseded documents were retained only to explain historical practice or edition transitions.

Comparative tables contain numerical criteria only when the descriptor, receptor, frequency treatment, exposure rule and decision meaning were verifiable from a primary or authorized source. Unverified national values are reported as evidence gaps rather than as proof that no provision exists.

Each criterion was extracted as a complete record using the fields in Table 1. KB denotes the German frequency-weighted vibration index, whereas VdB denotes a logarithmic RMS vibration velocity level. Both descriptors are defined in Section 5.

Table 1 Minimum fields for cross-country comparison of environmental-vibration criteria

Field	Required information
Instrument	Jurisdiction or geographical scope, issuing body, document title, edition, year, legal or administrative status
Source	Road, railway, metro/tram, construction, tunnelling, blasting
Receptor	People, buildings and structures, vibration-sensitive facilities, equipment or activities
Measurement descriptor	Acceleration, velocity, PPV, RMS, VDV, KB, VdB, L_{aw} and spectral measures
Signal treatment	Frequency range, weighting, filtering, integration, vector or component rule, event definition
Context	Building use, room, measurement position, axis, day, evening or night period
Decision meaning	Limit value, guideline value, assessment value, action level, perception threshold, annoyance criterion, damage threshold

4. SOURCE-PATH-RECEPTOR FRAMEWORK

Environmental vibration is a source–path–receptor problem: response depends on excitation, the dynamic properties of the ground and structures, and the protected outcome. Equal source distances or equal measured amplitudes do not imply equivalent impacts when frequency content, duration, recurrence or measurement position differ [1,5–7,22–24].

Road vibration is dominated by tyre–road interaction, rail vibration by wheel–rail excitation, and construction or blasting by transient, repetitive or continuous ground excitation. Propagation may include pavement or track, tunnels, soil or rock, foundations and building elements. Receptors comprise occupants, conventional or heritage structures, and sensitive equipment; their corresponding outcomes and temporal characteristics are summarized in Table 2.

Table 2 Principal source–path–receptor combinations and temporal characteristics covered by the review

Source class	Principal excitation	Temporal character	Principal propagation path	Typical receptor and outcome
Road traffic	Dynamic tyre–road forces, particularly from heavy vehicles and pavement irregularities	Recurrent individual pass-bys	Pavement, soil and foundations	Building occupants: perception and annoyance; vibration-sensitive uses
Surface railway	Wheel-rail roughness, joints, defects and dynamic axle loads	Recurrent discrete events	Track, formation, soil, foundations and building structure	Occupants: perception and annoyance; buildings; sensitive equipment
Tram and light rail	Wheel-rail interaction, track irregularities, switches and embedded track	Frequent recurrent events	Track slab or street structure, soil, foundations and building structure	Occupants; ground-borne noise; sensitive facilities
Underground metro	Wheel-rail interaction within a tunnel	Frequent recurrent events	Track, tunnel structure, surrounding ground, foundations and receiving building	Occupants: vibration and ground-borne noise; sensitive facilities and equipment
Construction	Piling, compaction, excavation, demolition and tunnelling	Transient, repetitive or continuous	Ground, foundations and temporary or permanent structures	Occupants; cosmetic or structural damage; sensitive facilities
Blasting	Rapid release of explosive energy	Short-duration impulsive events	Rock or soil, foundations and air	Occupants; buildings and heritage structures

5. VIBRATION QUANTITIES AND ASSESSMENT FAMILIES

5.1 Acceleration and frequency weighting

Human sensitivity depends on frequency and direction. ISO 2631-2:2026 therefore applies the W_m weighting from

1 Hz to 80 Hz [21]. Frequency weighting W_m for the evaluation of vibration in buildings is shown in Fig. 1. The curve was generated by the authors from the one-third-octave representation of the W_m frequency weighting retained in ISO 2631-2:2026 [21].

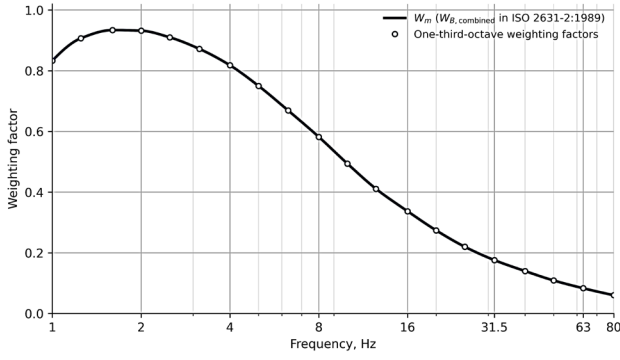


Fig. 1 Frequency weighting for the evaluation of vibration in buildings

The frequency-weighted root-mean-square (RMS) acceleration is calculated as:

$$a_w = \sqrt{\frac{1}{T} \int_0^T a_w^2(t) dt}, \quad (1)$$

where $a_w(t)$ is W_m -weighted acceleration and T is the evaluation period.

For one-third-octave RMS accelerations a_i , the corresponding weighted overall value is:

$$a_w = \sqrt{\sum_i (W_{m,i} a_i)^2}, \quad (2)$$

where $W_{m,i}$ is the weighting factor for band i .

A single weighted value conceals spectral distribution. Therefore, weighting, range, axis, location, duration and processing should be reported with the spectrum where available [21].

5.2 RMS, running RMS and maximum time-weighted values

RMS describes effective magnitude over a stated interval but is incomplete without the measured quantity, weighting, integration time and event rule [3,5,21]. Long averages suit stationary vibration but can dilute short train, construction or blasting events. For time-varying vibration, a running RMS value can be calculated repeatedly using a moving time window of duration τ :

$$a_{w,rms}(t_0) = \left[\frac{1}{\tau} \int_{t_0-\tau}^{t_0} a_w^2(t) dt \right]^{1/2}, \quad (3)$$

where $a_w(t)$ is weighted acceleration, τ the integration time and t_0 the end of the window.

Its maximum is:

$$a_{w,max} = \max_{t_0} [a_{w,rms}(t_0)]. \quad (4)$$

This value may be reported as the maximum transient vibration value (MTVV). Comparisons require identical integration time, weighting and event selection; repeated-event statistics must also be stated.

A result should identify whether it represents whole-record RMS, event RMS, running RMS, MTVV or a statistic from several events. RMS-based criteria are comparable only when these definitions and measurement conditions coincide.

5.3 Vibration dose value

VDV is a fourth-power cumulative measure for intermittent or impulsive weighted acceleration and is more sensitive to peaks than RMS [3]:

$$VDV = \left[\int_0^T a_w^4(t) dt \right]^{1/4}, \quad (5)$$

where $a_w(t)$ is weighted acceleration and T is the exposure period; VDV is expressed in $m/s^{1.75}$.

For multiple events, dose increases with magnitude and recurrence and may be combined as:

$$VDV_{total} = \left[\sum_{j=1}^N VDV_j^4 \right]^{1/4}, \quad (6)$$

where VDV_j is the dose of event j and N is the number of events.

5.4 Velocity, PPV and vibration velocity level

PPV, prominent in construction, blasting and structural guidance, is the maximum absolute instantaneous particle velocity in a stated direction [2,4,6,24]. PPV is normally reported in mm/s with direction, frequency range, position and processing; frequency-dependent building categories must also be stated [2,4,6,18].

Rail and metro assessments commonly use RMS velocity over interval T :

$$v_{rms} = \left[\frac{1}{T} \int_0^T v^2(t) dt \right]^{1/2}. \quad (7)$$

The corresponding logarithmic vibration velocity level is:

$$L_v = 20 \log_{10} \left(\frac{v_{rms}}{v_{ref}} \right), \quad (8)$$

where v_{ref} is the reference velocity. FTA VdB uses $1 \mu\text{in/s}$ ($2.54 \times 10^{-8} \text{ m/s}$) [5].

PPV and VdB are not directly convertible without the waveform, spectrum, crest factor and evaluation rule.

5.5 KB assessment

DIN 4150-2 evaluates people using dimensionless, frequency- and time-weighted KB indices based primarily on velocity from 1 Hz to 80 Hz [8]. The maximum time-dependent severity is:

$$KB_{Fmax} = \max_t [KB_F(t)]. \quad (9)$$

$KB_F(t)$ is the running RMS value of the frequency-weighted vibration signal evaluated using the Fast time weighting (time constant 0.125 s).

The decision compares KB_{Fmax} with lower and upper guideline values A_u and A_0 :

$$KB_{Fmax} \leq A_u \Rightarrow \text{requirements satisfied}, \quad (10)$$

$$KB_{Fmax} > A_0 \Rightarrow \text{requirements not satisfied}, \quad (11)$$

and, for the intermediate range,

$$A_u < KB_{Fmax} \leq A_0, \quad (12)$$

acceptability depends on

$$KB_{FT_r} \leq A_r. \quad (13)$$

A_u , A_0 and A_r are guideline values rather than universal statutory limits and depend on source, period and building use. They must not be confused with DIN 4150-3 structural criteria.

DIN 4150-2:2025-08 supersedes the 1999 edition; earlier procedures and values require edition verification [8].

5.6 One-third-octave spectra and ground-borne noise

One-third-octave spectra retain information needed for rail diagnosis and sensitive-equipment assessment [1,5,10,22,23]. Band RMS velocity is:

$$v_{\text{rms},i} = \left[\frac{1}{T} \int_0^T v_i^2(t) dt \right]^{1/2}, \quad (14)$$

where $v_i(t)$ is band-filtered velocity.

Its logarithmic level is:

$$L_{v,i} = 20 \log_{10} \left(\frac{v_{\text{rms},i}}{v_{\text{ref}}} \right), \quad (15)$$

where the specified reference velocity must be reported.

Spectra identify wheel-rail excitation, resonances, propagation losses and building amplification and should be reported with range, bandwidth, averaging, direction and position [1,5,10,22,23].

Ground-borne noise is sound radiated by vibrating room surfaces and is expressed as sound-pressure level:

$$L_p = 20 \log_{10} \left(\frac{p_{\text{rms}}}{p_{\text{ref}}} \right), \quad (16)$$

where p_{rms} is RMS pressure and $p_{\text{ref}} = 20 \mu\text{Pa}$.

Vibration and sound levels use different physical quantities and references and they must be assessed and reported separately [1,5,7].

6. INTERNATIONAL AND WIDELY USED NATIONAL REFERENCE FRAMEWORKS

ISO 2631-2:2026 specifies building-vibration measurement and simulation for comfort and annoyance, including W_m weighting from 1 Hz to 80 Hz [21]. It does not prescribe universal limits. Annex C provides exposure-response relationships, while national or project criteria remain necessary.

ISO 14837-1 covers ground-borne vibration and noise from rail systems; ISO/TS 14837-31 addresses field measurement for human exposure, and ISO/TS 14837-32 dynamic ground properties [1,22,23]. They support consistent characterization but establish no global acceptance limit.

ISO 4866:2010 gives measurement principles for fixed structures exposed to traffic, construction, piling and blasting but does not prescribe a universal damage limit [24].

DIN 4150-2:2025-08 assesses people through source- and period-dependent KB procedures, whereas DIN 4150-

3 addresses structural effects using PPV and frequency-dependent guidance [2,6,8].

BS 6472-1 uses weighted RMS and VDV for human response; BS 7385-2 uses PPV and frequency-dependent guidance for building damage [3,4]. Their legal force depends on incorporation into approvals, permits or contracts.

The FTA manual integrates screening and detailed rail assessment, separately addressing ground-borne vibration, ground-borne noise, event frequency, sensitive land uses and construction [5]. It is included as a transparent methodological benchmark for metro projects.

7. COMPARATIVE ASSESSMENT CRITERIA AND NATIONAL FRAMEWORKS

Verified values are compared only within their original descriptors and decision functions. Tables 3–6 present British and FTA criteria, whereas Tables 7–11 summarize European institutional frameworks and verified Dutch, Spanish and Czech values. Missing authorized numerical evidence is recorded explicitly.

7.1 British and FTA criteria

BS 6472-1:2008 provides guidance for evaluating the likelihood of adverse comment using vibration dose value (VDV). For residential buildings, it distinguishes a 16 h daytime assessment period and an 8 h night-time assessment period [3]. The ranges in Table 3 indicate the expected probability of adverse comment from building occupants and do not constitute statutory environmental limits. Individual sensitivity, source characteristics, prior exposure, expectations and the situational context can influence the observed response.

BS 7385-2 uses peak component particle velocity (PPV) and frequency-dependent guide values for assessing the onset of cosmetic damage due to transient vibration [4]. The values in Table 4 apply to the component predominant in the frequency range of concern. The values indicate the onset of cosmetic damage from transient vibration, whereas structural damage generally requires higher amplitudes. They are not thresholds for human perception and do not represent a sharp boundary between absolute safety and damage. The standard does not provide corresponding guide values below 4 Hz, where displacement-related effects can become increasingly important. Lower values can be appropriate for continuous vibration because repeated loading can increase the possibility of fatigue-related effects, while protected, historic or unusually fragile structures require case-specific assessment [4].

The FTA general assessment for railway and metro systems is event-based and distinguishes land use and the number of daily vibration events. Frequent events are more than 70 events per day, occasional events are 30 to 70 events per day, and infrequent events are fewer than 30 events per day [5]. Rapid-transit and metro services typically fall within the frequent-event category. Under the general assessment procedure, impact is identified when the predicted indoor vibration or ground-borne-noise level exceeds the applicable criterion in Table 5 [5].

In the FTA framework, GBV is reported in VdB using Eq. (8), with $v_{\text{ref}} = 1 \mu\text{m/s} = 2.54 \times 10^{-8} \text{ m/s}$. Ground-borne noise (GBN) is reported as the A-weighted indoor sound-pressure level L_{pA} , obtained by applying A-weighting to the frequency components of the sound-pressure level defined in Eq. (16), with $p_{\text{ref}} = 20 \mu\text{Pa}$ [5]. Although both are expressed logarithmically, they represent different physical quantities and are evaluated independently.

The FTA manual for special building criteria recognizes that studios, concert halls, auditoriums and theatres require activity-specific criteria shown in Table 6 [5]. These values demonstrate why a single

residential threshold is inadequate for metro planning in mixed-use urban areas. Detailed spectral or project-specific criteria can be necessary where an A-weighted ground-borne-noise level does not adequately represent interference with the intended activity.

British VDV integrates fourth-power acceleration over a day or night, whereas FTA VdB is a maximum-event RMS velocity level classified by daily event count [3,5]. BS 7385-2 PPV instead concerns cosmetic-damage onset [4]. These values cannot be converted or ranked without the original time history and complete method.

Table 3 BS 6472-1 residential VDV ranges in $\text{m/s}^{1.75}$ and probability of adverse comment

Place and period	Assessment period	Low probability of adverse comment	Adverse comment possible	Adverse comment probable
Residential, day	07:00-23:00 (16 h)	0.2 ÷ 0.4	0.4 ÷ 0.8	0.8 ÷ 1.6
Residential, night	23:00-07:00 (8 h)	0.1 ÷ 0.2	0.2 ÷ 0.4	0.4 ÷ 0.8

Table 4 BS 7385-2 peak component particle velocity (PPV) guide values for the onset of cosmetic damage due to transient vibration

Building category	4-15 Hz	15 Hz and above
Reinforced or framed structures; industrial and heavy commercial buildings	50 mm/s	50 mm/s
Unreinforced or light-framed structures; residential or light commercial buildings	15 mm/s at 4 Hz, increasing to 20 mm/s at 15 Hz	20 mm/s at 15 Hz, increasing to 50 mm/s at 40 Hz and above

Table 5 FTA indoor ground-borne vibration and noise impact criteria

Land-use category	GBV frequent / occasional / infrequent (VdB)	GBN frequent / occasional / infrequent (dBA)
Category 1: vibration-sensitive interior operations	65 / 65 / 65	Not generally applicable
Category 2: residences and buildings where people normally sleep	72 / 75 / 80	35 / 38 / 43
Category 3: institutional land uses, primarily daytime	75 / 78 / 83	40 / 43 / 48

Table 6 FTA criteria for selected special buildings

Room	GBV frequent / occasional or infrequent (VdB)	GBN frequent / occasional or infrequent (dBA)
Concert halls	65 / 65	25 / 25
Television studios	65 / 65	25 / 25
Recording studios	65 / 65	25 / 25
Auditoriums	72 / 80	30 / 38
Theatres	72 / 80	35 / 43

7.2 German, Dutch and Swiss assessment frameworks

Germany, the Netherlands and Switzerland provide three methodologically distinct examples of environmental-vibration assessment. German practice separates KB-based human assessment from structural PPV criteria, the Dutch

SBR framework uses complementary v_{max} and v_{per} indices, whereas Switzerland assesses railway vibration and structure-borne sound within a single source-specific framework [2,8,10–12]. Table 7 summarizes the principal institutional and methodological characteristics of these approaches.

Table 7 Institutional and methodological comparison of the German, Dutch and Swiss frameworks

Country	Instrument	Primary receptor	Regulatory function	Evidence basis
Germany	DIN 4150-2:2025-08 [8]	People in buildings	Current national standard; source-specific assessment includes period and recurrence	Official standards catalogue and current standard
Germany	DIN 4150-3:2016-12 [2]	Buildings and structures	National structural-vibration standard used in construction practice	Official standards catalogue
Netherlands	SBR Parts A, B and C [10]	Damage, people and equipment	Technical guidelines referenced in environmental rules, policy and decisions	Government explanation and guideline records
Netherlands	Rail-vibration policy rule [11]	People near main railway projects	Rail-specific policy aligned with SBR Part B and proportional mitigation	Government source
Switzerland	BEKS (1999) [12]	Rail vibration and structure-borne sound	Transitional administrative instrument for railway installations	Federal environmental source

DIN 4150 separates effects on people from effects on structures. DIN 4150-2:2025-08 addresses people in buildings through the KB assessment framework and supersedes the 1999 edition [8]. The revision is methodologically important because values and procedures copied from older research or environmental reports cannot automatically be presented as current German criteria. The 1999 and 2025 editions must therefore be treated as separate historical and current records. DIN 4150-3:2016-12 is the companion reference for structural effects [2]. The two parts use different descriptors, measurement positions and decision criteria and are not interchangeable.

Information published by the Government of the Netherlands identifies SBR Part B as a principal basis for measuring and assessing vibration nuisance in buildings [10]. The method uses complementary descriptors: $v_{\max}$ represents the maximum expected vibration strength in a room, whereas v_{per} represents vibration exposure over the assessment period. This dual structure retains information about both individual high-magnitude events and longer-term exposure.

The SBR guidelines are not legislation in themselves. Their measurement methods and SBR-derived assessment values nevertheless enter environmental rules, railway policy, planning decisions and project conditions [10,11]. The SBR family separates Part A for damage to buildings, Part B for human annoyance and Part C for interference with equipment. This explicit receptor separation is a useful model for cross-country comparison.

The national Rail Vibration Policy Rule (Beleidsregel trillinghinder spoor) provides a verified numerical application of the SBR Part B descriptors for route decisions concerning the construction, alteration or renewed use of national railway infrastructure [11]. It defines A1 as the target value for $v_{\max}$, A2 as the limit value for $v_{\max}$ and A3 as the limit value for v_{per} . Applicability depends on building function, period and whether the situation is new or existing [11]. Day, evening and night are defined as 07:00–19:00, 19:00–23:00 and 23:00–07:00, respectively. Table 8 preserves the distinction between new and existing situations and between maximum and period exposure.

Table 8 Dutch railway-vibration target and limit values for people in buildings

Situation	Building function	Period	A1: $v_{\max}$ target	A2: $v_{\max}$ limit	A3: v_{per} limit
New	Health care and residential	Day/evening	0.10	0.40	-
New	Health care and residential	Night	0.10	0.20	-
New	Education, offices and assembly	Day/evening	0.15	0.60	-
New	Education, offices and assembly	Night	0.15	0.60	-
New	Critical workspace	Day/evening	0.10	0.10	-
New	Critical workspace	Night	0.10	0.10	-
Existing	Health care and residential	Day/evening	0.20	0.80	0.10
Existing	Health care and residential	Night	0.20	0.40	0.10
Existing	Education, offices and assembly	Day/evening	0.30	1.20	0.15
Existing	Education, offices and assembly	Night	0.30	1.20	0.15
Existing	Critical workspace	Day/evening	0.10	0.10	-
Existing	Critical workspace	Night	0.10	0.10	-

Swiss railway practice is notable for evaluating mechanical vibration and structure-borne sound within the same source-specific framework. Federal environmental documentation identifies the 1999 instruction for assessing vibration and structure-borne sound from railway installations (BEKS) as a transitional administrative instrument [12]. Its railway-specific source-path-receiver approach is methodologically relevant to metro assessment, although its field of application and administrative status must be distinguished from those of general building-vibration standards.

7.3 Other selected European national approaches

Spain, Austria, the Nordic countries, Poland and the Czech Republic illustrate several distinct ways of translating vibration measurements into planning, comfort, structural or public-health decisions. Their approaches are considered in three groups below so that differences in receptor coverage, assessment descriptors and regulatory status remain explicit.

Table 9 identifies the verified scope and status of selected instruments.

Table 9 Selected Spanish, Austrian, Nordic and Central European assessment instruments

Country	Principal instrument	Source and receptor scope	Assessment logic	Status and evidence basis
Austria	ÖNORM S 9012:2016 [13]	Rail and road traffic; people and structure-borne sound	Vibration immission and secondary airborne noise	Current national standard; official catalogue
Sweden	SS 4604861:2022 [14]	Principally traffic vibration; comfort in dwellings and offices	Measurement and comfort guideline values; not structural damage	Current replacement edition; official catalogue
Norway	NS 8176:2017 [15,25]	Road and rail traffic; people in buildings	Statistical maximum velocity or acceleration and comfort classes	National standard; catalogue framework
Finland	VTT guidance [16]	Road and rail traffic; people and building planning	Vibration classes and planning-oriented assessment	Technical guidance; non-statutory
Poland	PN-B-02171:2017-06 [17,19]	Externally generated vibration; people in buildings	Basic RMS method, additional VDV method and human vibration perceptivity ratio (HVPR) index	National standard; methods verified

Table 9 Selected Spanish, Austrian, Nordic and Central European assessment instruments (continued)

Country	Principal instrument	Source and receptor scope	Assessment logic	Status and evidence basis
Poland	PN-B-02170:2016-12 [18]	Traffic and other ground-borne sources; buildings and equipment	Frequency-band structural response and Scales of Dynamic Influence (SWD) assessment	National standard; framework verified
Czech Republic	Government Regulation No. 272/2011, as amended [20]	Environmental and building vibration; human health	Binding public-health framework for noise and vibration	Legal instrument and amendments verified
Spain	Real Decreto 1367/2007 [26]	Environmental and infrastructure vibration; people in habitable building interiors	L_{aw} , maximum W_m -weighted 1 s running RMS; stationary and transient-event compliance rules	Legally binding national regulation; official consolidated text

Spain provides a legally binding national framework for vibration in habitable building interiors. Real Decreto 1367/2007 applies the index $L_{aw} = 20 \log_{10}(a_w/a_0)$, where a_w is the maximum 1 s exponentially averaged W_m -weighted RMS acceleration and $a_0 = 10^{-6}$ m/s². L_{aw} is therefore a maximum-running-RMS or MTVV-type descriptor rather than an average over the complete assessment period. Annex II, Table C establishes the limit values reproduced in Table 10 [26].

Table 10 Spanish limit values for vibration in habitable indoor spaces

Building use	Limit L_{aw} (dB)
Residential	75
Hospital	72
Educational or cultural	72

For stationary vibration, no L_{aw} value may exceed the applicable limit. Transient vibration is assessed separately for daytime (07:00–23:00) and night-time (23:00–07:00): no exceedance is permitted at night, a daytime event may not exceed the limit by more than 5 dB and the weighted daytime exceedance count may not exceed nine. Events up to 3 dB above the limit count once and larger exceedances count three times. Measurements are made on the floor at the position and time of greatest annoyance, with direction, background vibration and repeated events addressed explicitly [26].

ÖNORM S 9012:2016 addresses human exposure in buildings to vibration immissions from land-based rail and road traffic and explicitly includes secondary airborne noise radiated by building elements [13]. This combined scope is particularly relevant to tram and metro projects,

for which assessment based only on mechanical vibration can overlook audible re-radiated sound.

SS 4604861:2022 provides measurement guidance and comfort-oriented values for vibration in buildings and is not intended for assessing damage to buildings or structures [14]. A separate structural assessment is therefore required when construction or blasting damage is at issue. NS 8176:2017 was developed specifically for measuring, assessing and classifying vibration in buildings from land-based transport [25]. Its methodological basis and dose–response classification system are described in the supporting research [15]. Its statistical maximum response and comfort classes differ from both long-period VDV assessment and the event-frequency categories used by the FTA.

Finnish transport-vibration classes developed through VTT research are treated as technical planning guidance rather than nationally binding statutory limits [16].

Poland maintains a two-standard division between human and structural response. PN-B-02171:2017-06 evaluates effects on people in buildings using a basic RMS method, an additional VDV method and the human vibration perceptivity ratio (HVPR) [17,19]. PN-B-02170:2016-12 addresses harmful effects on buildings and equipment through frequency-band structural-response assessment using the Polish Scales of Dynamic Influence (SWD) [18]. This distinction must be retained when Polish results are compared with DIN 4150-3 or BS 7385-2 [2,4].

Czech Government Regulation No. 272/2011, as amended, provides binding indoor public-health vibration limits [20]. The base value is $L_{aw,T} = 75$ dB, equivalent to $a_{ew,T} = 0.0056$ m/s². Appendix 5 corrections depend on source and time pattern (Table 11) [20]. Corrections apply to the base value; combined corrections are limited to +20 dB [20].

Table 11 Czech corrections to the base hygienic vibration limit in protected indoor spaces

Protected indoor space	Period	Continuous/intermittent correction (dB)	Factor	Repeated-shock correction (dB)	Factor
Operating rooms	Day	0	1	0	1
Operating rooms	Night	0	1	0	1
Living rooms	Day	+6	2	+24	16
Living rooms	Night	+3	1.41	+3	1.41
Hospital rooms	Day	+6	2	+24	16
Hospital rooms	Night	+3	1.41	+3	1.41
Lecture/class and preschool/school rooms	Day	+6	2	+24	16
Lecture/class and preschool/school rooms	Night	+3	1.41	+3	1.41
Other protected indoor spaces	Continuous	+12	4	+42	128

7.4 South-eastern Europe and unresolved evidence gaps

Within the primary and official sources reviewed, no single consolidated environmental-vibration instrument was verified for Slovenia, Croatia, Serbia or Montenegro that is directly equivalent in scope to DIN 4150-2, SBR Part B or the Czech public-health regulation and simultaneously addresses road, railway, metro and construction sources. Environmental studies can instead rely on adopted ISO or national standards, construction- or blasting-specific documents, foreign engineering criteria, permit conditions and expert judgement. This finding identifies an unresolved evidence gap and does not demonstrate that no relevant sectoral or local provision exists.

Serbia and Montenegro are therefore reported as separate evidence-gap cases. Formally adopted SRPS or MEST standards must be distinguished from foreign standards used only as engineering references. Where a binding numerical environmental-vibration criterion could not be verified from the reviewed primary sources, the comparison records an unresolved regulatory evidence gap rather than assuming either the presence or absence of an applicable national provision.

7.5 Evidence status and limitations of direct comparison

Results are classified as verified numerical criteria, verified institutional frameworks or unresolved evidence gaps. Catalogue records establish scope and edition but not unverified values; secondary values are contextual only.

Equal numbers do not imply equivalent protection when descriptors, references, locations, periods or legal

functions differ. Tables therefore retain units, receptor and decision meaning.

8. METHODOLOGICAL CONVERGENCE AND DIVERGENCE

8.1 Areas of convergence

Systems converge on receptor separation, frequency relevance, explicit measurement position and different treatment of recurrent transport and transient construction events [2–6,8,10,15,17,18,21]. Human response generally begins well below damage levels, and metro frameworks increasingly assess vibration and re-radiated noise in parallel [1,3–5,12,13,17–19].

8.2 Areas of divergence

They diverge in descriptor and exposure logic: British VDV integrates intermittent acceleration, German KB uses source- and period-dependent indices, Dutch $v_{\max}/v_{\text{per}}$ combines maxima and exposure, Spanish L_{aw} applies statutory maximum-running RMS and event rules, FTA uses event VdB and event frequency, whereas Nordic and Polish systems use other statistical or perceptibility-based approaches [3,5,8,10,11,15,17–19].

Table 12 summarises the physical meaning, time treatment and comparability conditions of the principal descriptors used by the reviewed assessment systems. Legal status also differs among legislation, incorporated standards, administrative values and voluntary guidance. These categories must not be labelled collectively as statutory limits [10,11,14,20,26].

Table 12 Comparability of the principal environmental-vibration descriptors

Descriptor	Primary purpose	Time treatment	Typical unit	Condition for comparison
Weighted RMS acceleration	Human comfort and annoyance	Quadratic mean over a specified interval	m/s ²	Weighting, axis, interval and measurement location must be identical
VDV	Human response to intermittent exposure	Fourth-power integration over the complete exposure period	m/s ^{1.75}	Not directly comparable with RMS without the time history or additional exposure information
PPV	Building response and damage screening	Maximum instantaneous particle velocity	mm/s	Component rule, frequency range, measurement position and building class must be equivalent
KB indices	People in buildings	German frequency weighting and time-dependent evaluation	Dimensionless index	Not directly convertible to VDV, PPV or VdB
$v_{\max}$ and v_{per}	People in buildings	Maximum expected response combined with period exposure	Dimensionless standard-specific indices	Comparable only when determined using the same SBR procedure and decision context
VdB	Rail and metro event response	Maximum event-based RMS velocity level	dB relative to a specified reference velocity	Reference velocity, bandwidth, averaging procedure and event rule must match
One-third-octave velocity	Sensitive equipment, diagnosis and rail-transmission assessment	Band-specific RMS spectrum	µm/s or dB	Spectra may be compared only band by band using equivalent bandwidths and reference quantities
Ground-borne noise	Audible indoor response generated by structural vibration	Event-based maximum or equivalent indoor sound-pressure level	dBA or frequency-band levels	Must be evaluated as an acoustic quantity and not treated as a mechanical-vibration level
L_{aw} (Spain)	People in habitable building interiors	Maximum 1 s W_m -weighted running RMS; separate event rules	dB re 10 ⁻⁶ m/s ²	Comparable only when weighting, time constant, measurement position and event rule are aligned

8.3 Consequences for cross-country comparison

Direct ranking is valid only for the same receptor, source, descriptor, frequency treatment, exposure rule, measurement position and legal function. Identical mm/s values can represent PPV or RMS velocity, while decibel values may use different physical references.

Dutch dimensionless indices, Spanish and Czech weighted-acceleration limits, British VDV and FTA VdB illustrate why even well-defined national criteria cannot be converted without time histories and spectra [3,5,11,20,26].

Comparison should first address institutional and methodological features, then numerical values within homogeneous descriptor families. Non-equivalence should be reported rather than removed through assumed conversion.

9. PROPOSED MINIMUM REPORTING FRAMEWORK

To improve transparency and reproducibility, this review proposes a minimum reporting framework for every environmental-vibration criterion included in a comparative assessment. The framework extends the extraction fields introduced in Table 1 and converts them into explicit reporting requirements. A criterion for which one or more mandatory fields cannot be verified may still be described as contextual evidence, but it should not be included in a direct cross-country numerical comparison. Missing information should be stated explicitly and reflected in the assigned evidence status.

Table 13 presents the proposed minimum dataset. The framework is intended to prevent numerical criteria from being separated from the measurement procedures, receptors and decision rules that define their physical and regulatory meaning.

Table 13 Proposed minimum reporting framework for environmental-vibration criteria

Field	Information to report	Reason for inclusion
Identification	Country, issuing body, document title and number, edition, publication year and amendment status	Prevents the use of superseded or incorrectly attributed criteria
Regulatory status	Law, regulation, incorporated standard, voluntary standard, administrative guideline, planning condition, permit requirement or contract condition	Distinguishes a legal obligation from technical or professional guidance
Source	Road traffic, conventional railway, metro, tram or light rail, construction, tunnelling, demolition or blasting	Prevents inappropriate transfer between dissimilar excitation types
Receptor	People, buildings or structures, heritage buildings, vibration-sensitive equipment or vibration-sensitive activities	Links the criterion to the protected outcome
Building context	Building use, room function, occupancy, structural class, condition and heritage status	Accounts for differences in human sensitivity and structural vulnerability
Quantity and unit	Measured physical quantity and assessment descriptor, including acceleration or velocity, RMS, VDV, PPV, KB, VdB, L_{aw} , v_{max} , v_{per} or frequency-band spectrum	Defines the physical and mathematical meaning of the reported value
Signal processing	Frequency range, frequency weighting, filters, measurement axes, component or vector rule, averaging or integration procedure, time constant and reference quantity for logarithmic levels	Enables reproducible calculation and prevents comparison of differently processed signals
Exposure rule	Event definition, assessment duration, number and recurrence of events, statistical rule and applicable day, evening or night period	Distinguishes isolated events, recurrent events and cumulative exposure
Measurement position	Ground, tunnel, foundation, load-bearing wall, building floor, floor center, room or occupied position	Accounts for propagation and building-response amplification
Operating and environmental conditions	Source operating condition, speed or load, source-receiver distance, ground conditions and other relevant measurement conditions	Defines the conditions under which the criterion or measured value applies
Decision meaning	Target, guideline, assessment, action or limit value, including whether it concerns perception, annoyance, interference, cosmetic damage or structural damage	Prevents criteria with different decision functions from being combined
Compliance and uncertainty rule	Treatment of measurement or prediction uncertainty, rounding, statistical confidence and exceedance procedure	Clarifies how compliance or non-compliance is determined
Evidence status and source locator	Primary text, authorized reproduction, official application, official summary or secondary source, together with the relevant clause, table or page	Makes evidential confidence explicit and permits independent verification

10. DISCUSSION

European practice is technically developed but institutionally fragmented. Convergence exists in receptor separation and the treatment of frequency, position and duration. Divergence lies in descriptor, time integration, event recurrence, building classification, ground-borne-noise treatment and legal status.

The retained numerical examples demonstrate distinct decision functions: British VDV addresses adverse-

comment probability, BS 7385-2 PPV cosmetic damage, FTA VdB event impact, Dutch v_{max}/v_{per} railway decisions, Spanish Law limits and Czech weighted-acceleration public-health compliance [3–5,11,20,26]. None is an alternative label for the same quantity.

Metro projects require joint but separate vibration and noise assessment; construction and blasting require separation of occupant response from damage screening.

Legal status and document edition are as important as magnitude [2–6,8,10–13,18].

The proposed reporting matrix is the main practical result. It preserves traceability and supports comparison without forcing conversion between incompatible metrics. Incomplete access to authorized national texts, particularly in south-eastern Europe, remains a limitation; unresolved values are therefore reported as evidence gaps rather than replaced with foreign criteria.

11. CONCLUSIONS

Environmental-vibration systems share core physical principles but remain heterogeneous in method and authority. National values are comparable only after alignment of source, receptor, descriptor, unit, frequency treatment, exposure rule, location, building use and decision meaning.

Verified British, FTA, Dutch, Spanish and Czech criteria represent internally coherent but non-equivalent approaches. Human-response, structural-damage and sensitive-use criteria must remain separate, while metro vibration and ground-borne noise require parallel assessment.

Table 13 provides a practical minimum dataset for environmental assessment and future European guidance. Further work should verify unresolved national instruments and develop comparable exposure–response evidence without discarding source- and receptor-specific information.

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STRATEGIC ENVIRONMENTAL NOISE MANAGEMENT: AN EVALUATION OF ACTION PLANNING AND THE CASE OF NOVI SAD AGGLOMERATION

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Abstract. *Environmental noise management in urban areas requires a transition from strategic noise mapping to the development and implementation of effective noise action plans. In Serbia, this process is still at an early stage. The draft Noise Action Plan for the Novi Sad Agglomeration, developed in 2025, is the first and, to date, the only noise action planning document prepared for an agglomeration in Serbia. It therefore provides an important case for examining the practical implementation of strategic environmental noise management at the national level. This paper critically evaluates the Novi Sad draft Action Plan within the framework established by Directive 2002/49/EC and contemporary approaches to environmental noise management. The analysis focuses on the proposed noise mitigation measures, protection of quiet areas, institutional and financial implementation challenges, and the potential integration of citizen perception, environmental health equity, and the noise footprint concept into action planning. The results identify both the strengths of the proposed planning framework and several areas requiring further development, particularly regarding implementation mechanisms, inter-sectoral coordination, financing, and broader criteria for evaluating the urban acoustic environment. The Novi Sad case provides a basis for discussing future noise action planning in other Serbian agglomerations and the further development of strategic environmental noise management in Serbia.*

Key words: *Environmental noise, Noise action plans, Environmental Noise Directive, Novi Sad, Strategic noise management, Serbia*

1. INTRODUCTION

Environmental noise is increasingly recognized as an important environmental and public health issue associated with urbanization and the continuing growth of road, rail, and air transportation. Long-term exposure to environmental noise is associated with a range of adverse health and well-being effects, including annoyance, sleep disturbance, cognitive effects in children, and increased cardiovascular risk [1,2]. Consequently, environmental noise management has become an important component of sustainable urban planning and environmental policy.

At the European level, a common framework for the assessment and management of environmental noise was established by Directive 2002/49/EC relating to the assessment and management of environmental noise, commonly referred to as the Environmental Noise

Directive (END) [3]. The Directive introduced a systematic approach based on strategic noise mapping and subsequent noise action planning. Strategic noise maps provide information on population exposure using common noise indicators, particularly L_{den} and L_{night} , while action plans are intended to address identified noise problems, manage environmental noise and its effects, and protect quiet areas against an increase in noise [3].

Experience gained during the implementation of the END has shown, however, that the preparation of strategic noise maps does not automatically result in effective noise reduction. The transition from noise exposure assessment to practical mitigation measures depends on institutional responsibilities, financial resources, integration with transport and spatial planning, and the capacity of competent authorities to implement and monitor proposed measures [4]. Recent European technical guidance therefore places increasing emphasis on the practical design and implementation of noise action plans and on the selection of measures addressing noise at the source, along the propagation path, and at the receiver [5].

At the same time, contemporary approaches to environmental noise management increasingly recognize that conventional assessment based predominantly on calculated or measured sound levels does not fully describe the quality of the urban acoustic environment. Citizen perception and noise complaints can provide additional information on local noise problems [6], while environmental health equity draws attention to differences in noise exposure and access to environmental benefits among population groups [7]. More recently, the noise footprint concept has been proposed as a broader, responsibility-based framework for assessing and communicating noise impacts beyond conventional source-receiver relationships and noise mapping, with the aim of incorporating noise more explicitly into environmental sustainability assessment [8]. However, the concept is still evolving and does not yet represent a standardized noise indicator or assessment metric [9]. These approaches can complement conventional strategic noise mapping and contribute to more comprehensive noise action planning.

In Serbia, the requirements for strategic noise mapping and action planning have been incorporated into the

national environmental noise protection framework [10,11]. However, practical implementation of noise action planning for agglomerations is still at an early stage. Following the preparation of strategic noise maps, the draft Noise Action Plan for the Novi Sad Agglomeration was developed in 2025 [12]. It represents the first and, to date, the only noise action planning document prepared for an agglomeration in Serbia. This gives the Novi Sad case particular relevance, not only for assessing local noise management measures but also for examining the challenges associated with the practical implementation of strategic environmental noise management in Serbia.

Against this background, the aim of this paper is to critically evaluate the draft Noise Action Plan for the Novi Sad Agglomeration within the END framework and contemporary environmental noise management approaches. The analysis considers the proposed mitigation measures, protection of quiet areas, institutional and financial implementation conditions, and opportunities for incorporating citizen perception, environmental health equity, and the noise footprint concept. Based on the identified strengths and limitations, the paper discusses recommendations that may support the further development and implementation of noise action planning in Novi Sad and provide useful experience for other Serbian agglomerations.

2. METHODOLOGY

The study employs a qualitative policy and document analysis supported by a comparative review of contemporary environmental noise-management literature. The principal sources comprise Directive 2002/49/EC (END) [3], Serbian environmental noise legislation [10,11], European Commission technical guidance for Noise Action Plans [5], WHO health-based guidance [2], relevant peer-reviewed literature [6–8], and the 2025 draft Action Plan for Noise Protection for the Novi Sad Agglomeration [12].

The analysis was conducted in three stages. First, the regulatory and policy framework was examined to identify the principal requirements and objectives relevant to strategic noise action planning, including mitigation of environmental noise, protection of quiet areas, public participation, and implementation responsibilities. Second, the Novi Sad draft Action Plan was examined with respect to four operational dimensions: (1) proposed noise-mitigation measures, (2) protection and management of quiet areas, (3) institutional responsibilities and inter-sectoral coordination, and (4) financing, implementation, and monitoring arrangements. The proposed measures were considered in relation to source-oriented, propagation-path, transport and spatial-planning, and receiver-oriented approaches described in contemporary European technical guidance [5].

Third, the conventional END-based assessment was complemented by three evaluation perspectives derived from recent literature: citizen perception and noise complaints [6], environmental health equity [7], and the noise footprint framework [8,9]. Citizen perception was considered as a potential complement to strategic noise indicators in identifying locally relevant noise problems

and community response. Environmental health equity was used to consider the distribution of noise exposure and mitigation benefits among population groups, while the noise footprint concept was examined as an evolving, complementary framework for considering acoustic impacts beyond conventional source–receiver relationships and noise mapping.

These criteria were applied qualitatively to identify the strengths, limitations, and implementation challenges of the Novi Sad draft Action Plan and to formulate recommendations for its further development. No new acoustic measurements or statistical re-analysis of the strategic noise-map database were performed. Numerical information was used only where it could be traced to the cited regulatory, planning, or scientific sources.

Fig. 1 summarizes the methodological framework and the relationship between the regulatory basis, operational evaluation dimensions, complementary evaluation perspectives, and the Novi Sad case study.

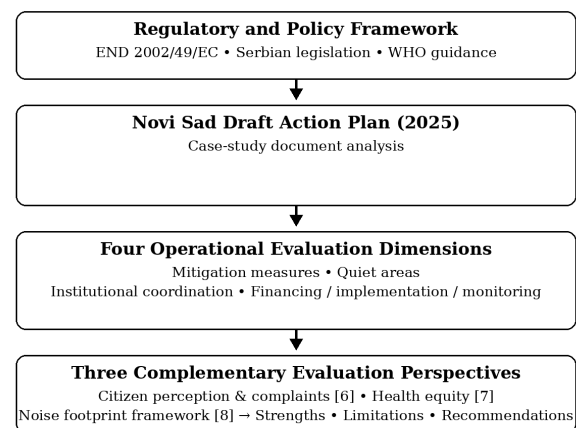


Fig. 1 Methodological framework for evaluating the Novi Sad draft Noise Action Plan

3. LITERATURE REVIEW AND EVALUATION FRAMEWORK

3.1. From Strategic Noise Mapping to Action Planning

The END established a common European framework in which strategic noise mapping is followed by action planning intended to manage environmental noise and its effects and to protect quiet areas [3]. Experience from the first implementation rounds nevertheless showed that technically advanced mapping does not by itself ensure effective mitigation. Important barriers include unclear institutional ownership, limited dedicated funding, and insufficient integration of noise objectives into transport and urban-development planning [4]. This implementation gap is particularly relevant when action plans are assessed not only by the measures they list, but also by the mechanisms through which those measures can be delivered and evaluated.

Recent European Commission guidance therefore treats action planning as a combination of source-oriented, propagation-path, transport and spatial-planning, receiver-oriented, and quiet-area measures [5]. The effectiveness of individual interventions is context dependent. For

example, the acoustic performance of low-noise road surfaces depends on pavement type, traffic composition, speed, maintenance, and ageing, while barriers require site-specific consideration of acoustic performance, access, safety, visual impact, and urban connectivity. Accordingly, expected noise reduction should be linked to defined locations, implementation conditions, responsibilities, time horizons, and post-implementation verification rather than expressed only as generic technical potential.

3.2. Operational Dimensions of Noise Action Planning

For the purposes of this study, the practical content of a noise action plan is considered through the four operational dimensions defined in the methodology: mitigation measures, protection and management of quiet areas, institutional responsibilities and inter-sectoral coordination, and financing, implementation, and monitoring. These dimensions reflect the transition from identifying exposure through strategic mapping to selecting, delivering, and evaluating interventions. They also provide the basis for distinguishing technically plausible measures from measures that are sufficiently specified for implementation.

Quiet-area protection has a particular role because the END requires action plans not only to address existing noise problems but also to preserve areas of favourable acoustic quality [3]. This implies that action planning should consider prevention as well as reduction. In practice, the designation and management of quiet areas benefit from transparent criteria that combine acoustic information with land use, accessibility, spatial context, and planning objectives. Likewise, implementation requires clearly assigned responsibilities, realistic financing, defined schedules, and measurable indicators that allow the effectiveness of adopted measures to be reviewed over time [5].

3.3. Complementary Evaluation Perspectives

The operational assessment can be broadened by perspectives that address aspects not fully represented by long-term strategic noise indicators. Jiao et al. [6] show that noise complaints and perceived annoyance are influenced by acoustic, contextual, spatial, and social factors. Complaint and perception data can therefore complement strategic indicators when local priorities are identified, although they should not replace objective acoustic assessment because reporting behaviour may differ among population groups and areas.

Environmental health equity provides a second complementary perspective. Riedel et al. [7] emphasize that noise exposure, access to quiet areas, and the benefits of mitigation may be distributed unevenly across socio-economic groups. Applying an equity lens to action planning therefore means examining not only where exposure is highest, but also whether mitigation resources and environmental benefits are distributed fairly. This perspective is especially relevant when priorities are established across heterogeneous urban areas.

The noise footprint provides a third complementary perspective. Rather than treating noise only as a direct source-receiver relationship or as a spatial distribution of

sound levels, the concept seeks to place noise within a broader environmental-footprint and sustainability framework [8]. This perspective draws attention to the wider consequences of human activities and choices that generate noise and to the distribution of responsibility for their acoustic impacts. In the context of noise action planning, such an approach could complement strategic noise maps by supporting a broader consideration of how transport, land-use, infrastructure, and other urban activities contribute to the acoustic environment. However, the current literature shows that definitions, metrics, and methodological approaches remain fragmented and that a unified standardized framework has not yet been established [9]. The noise footprint should therefore currently be regarded as a conceptual evaluation perspective rather than a regulatory or quantitative END indicator.

4. EVALUATION OF THE NOVI SAD DRAFT ACTION PLAN

4.1. Case Context and Regulatory Basis

Novi Sad, the capital of the Autonomous Province of Vojvodina and one of Serbia's largest urban agglomerations, provides a relevant case for examining the transition from strategic noise mapping to action planning. Its urban structure combines dense residential areas, major urban traffic corridors, rail infrastructure, commercial activities, and recreational spaces, creating a range of noise-management priorities. The 2025 draft Action Plan for Noise Protection for the Novi Sad Agglomeration was prepared following the city's strategic noise-mapping process [12]. In this evaluation, numerical claims are used only where they can be traced to the cited planning, regulatory, or scientific sources.

The draft Action Plan operates within Serbia's environmental noise framework. The Law on Environmental Noise Protection [10] requires strategic noise maps for agglomerations and provides for action plans in areas covered by strategic noise maps, with local self-government responsible for their preparation in cooperation with other competent entities. The Regulation on Noise Indicators and Limit Values [11] complements this framework by defining environmental noise indicators and outdoor limit values by acoustic zone. For health-based context, WHO [2] recommends reducing road-traffic noise below 53 dB L_{den} and 45 dB L_{night} ; these values are health-based guidelines and should not be interpreted as Serbian statutory limits.

4.2. Operational Evaluation of Proposed Measures

Following the methodology defined in Section 2, the draft Action Plan is evaluated through four operational dimensions: mitigation measures, quiet-area protection, institutional coordination, and financing, implementation, and monitoring. The purpose is not only to identify whether relevant measure categories are present, but also to assess whether they are sufficiently specified to support implementation and subsequent evaluation.

4.2.1 Noise-Mitigation Measures

The draft planning framework provides a basis for considering source-oriented, propagation-path, transport-management, spatial-planning, and receiver-oriented measures. Road traffic is a major management priority in the available planning context, making source and traffic-management measures particularly relevant. Low-noise road surfaces, speed and traffic-flow management, routing of heavy vehicles, modal shift, and integration with public transport and cycling policies are consistent with contemporary European action-planning practice [5]. Their practical value, however, depends on linking each measure to a clearly identified noise problem, candidate location, expected acoustic benefit, implementation time frame, and verification method.

Propagation-path measures such as noise barriers may be appropriate on selected transport corridors where source reduction and traffic-management measures are insufficient. Their feasibility requires site-specific acoustic modelling together with consideration of access, safety, visual impact, urban connectivity, and maintenance. Accordingly, barriers should be evaluated as part of a broader source-path-receiver strategy rather than as a generally applicable solution.

4.2.2 Protection and Management of Quiet Areas

Protection of quiet areas is an explicit element of the END framework [3]. In Novi Sad, parks, recreational areas, and other acoustically valuable spaces may form part of a systematic quiet-area strategy, but designation and protection should rely on transparent criteria and the applicable national and local framework. A stronger methodology would connect long-term sound levels with spatial context, accessibility, acoustic quality, land use, and clearly defined management objectives. In this sense, a quiet area should not be treated only as a location with comparatively low calculated noise levels, but as an urban resource whose acoustic quality is to be preserved against future deterioration. This would also make quiet-area protection easier to integrate with spatial and urban planning.

4.2.3 Institutional Coordination and Implementation Responsibilities

Implementation responsibilities for noise action planning are distributed across environmental, transport, spatial-planning, infrastructure, and public-utility authorities. The Serbian legal framework anticipates cooperation among competent entities [10]. The Novi Sad case therefore highlights the importance of assigning responsibilities to individual measures, defining coordination and reporting mechanisms, and establishing measurable implementation priorities. Without these elements, technically appropriate measures may remain difficult to deliver in practice.

4.2.4 Financing, Monitoring, and Evaluation

Measures such as specialized road surfaces, public-transport renewal, façade interventions, and barriers can require substantial investment. In the absence of a documented budget analysis, this paper does not infer a

specific funding shortfall. Instead, the evaluation criterion is whether major measures are connected to responsible funding sources, implementation phases, time horizons, and indicators for monitoring their acoustic effectiveness. Integration of noise mitigation into planned transport and infrastructure investment can improve feasibility, while external funding may complement established local and national responsibilities. For implementation purposes, each priority measure should therefore be accompanied by a minimum delivery record identifying the competent authority, supporting institutions, financing mechanism, implementation period, target area or source, expected acoustic effect, and a monitoring indicator. Such a record would allow subsequent revisions of the Action Plan to distinguish measures that have been implemented, delayed, modified, or shown to be ineffective.

4.3. Complementary Evaluation Perspectives

The three complementary perspectives introduced in Sections 2 and 3 provide an additional lens for assessing aspects of the urban acoustic environment that are not fully represented by conventional strategic indicators.

4.3.1 Citizen Perception and Complaints

END action planning includes public consultation, while recent research shows that complaint data and citizen perception can reveal local and contextual factors that are not fully captured by long-term indicators [6]. For Novi Sad, structured complaint analysis, digital reporting, or participatory mapping could complement formal consultation and acoustic monitoring, provided that such information is quality-controlled and interpreted together with objective exposure data. These tools are presented here as complementary planning instruments, not as substitutes for strategic noise mapping.

4.3.2 Environmental Health Equity

Environmental health equity provides a basis for examining whether noise exposure, access to quiet areas, and the benefits of mitigation measures are distributed unevenly across population groups [7]. Applying this perspective to future stages of Novi Sad action planning would require suitable socio-demographic and spatial data. The present qualitative analysis therefore identifies equity as a relevant evaluation dimension rather than claiming a demonstrated distributional inequality in Novi Sad.

4.3.3 Noise Footprint

The noise footprint framework broadens assessment beyond conventional contour mapping and direct source–receiver relationships by considering noise as an environmental impact associated with human activities and choices [8,9]. In the Novi Sad context, it may be useful as a complementary conceptual tool when evaluating quiet areas, spatial development, transport and infrastructure decisions, and cumulative acoustic pressures. Because a unified definition and standardized metric have not yet been established [9], its application should be regarded as a potential extension of conventional END-based assessment rather than an existing requirement of the draft Action Plan.

4.4. Synthesis of Strengths, Limitations, and Priorities

Overall, the Novi Sad draft Action Plan represents an important step from strategic noise mapping toward action planning in Serbia. Its principal strength is the establishment of a planning framework through which mitigation, quiet-area protection, institutional cooperation, and implementation can be addressed within the national END-related system. The critical issue for further development is the degree to which individual measures are translated into traceable and operational commitments.

The evaluation identifies four priorities. Major measures should be linked to specific noise problems and expected acoustic benefits, responsibilities and inter-sectoral coordination should be clearly defined, financing and implementation schedules should be accompanied by monitoring indicators, and transparent criteria should be developed for quiet-area protection. Citizen perception, environmental health equity, and the noise footprint can complement these operational priorities where appropriate data and institutional capacity are available. These perspectives should strengthen, rather than replace, the acoustic and regulatory basis of the Action Plan.

Table 1 Evaluation matrix for the Novi Sad draft Action Plan

Evaluation dimension	Main finding	Priority for further development
Mitigation measures	Relevant measure categories are available, but effectiveness depends on site-specific specification.	Link measures to identified problems, locations, expected acoustic benefit, time frame, and verification.
Quiet areas	Protection is recognized within the END framework, but operational designation requires transparent criteria.	Combine acoustic information with land use, accessibility, spatial function, and protection objectives.
Institutional coordination	Implementation involves several municipal and sectoral authorities.	Assign a lead authority and supporting entities to each major measure and define reporting arrangements.
Financing and monitoring	Technical feasibility alone does not ensure delivery.	Connect priority measures to financing, implementation phases, deadlines, and measurable monitoring indicators.
Complementary perspectives	Perception, equity, and noise footprint can add information beyond strategic indicators.	Introduce selectively where suitable data, methods, and institutional capacity are available.

5. DISCUSSION: IMPLICATIONS FOR FUTURE NOISE ACTION PLANNING IN SERBIA

5.1. From Action Plan to Implementation Cycle

The Novi Sad case has significance beyond the evaluation of a single planning document because it provides an initial practical reference for future noise action planning in Serbian agglomerations. The analysis indicates that the central challenge is not the identification of possible mitigation technologies, but the conversion of strategic-map information into a transparent implementation chain. Future plans would benefit from beginning with a documented link between the strategic noise map, priority exposure problems, selected measures, responsible institutions, financing, implementation deadlines, and indicators for post-implementation evaluation. This chain would make the planning process more traceable and would facilitate comparison between successive five-year planning cycles [3].

An implementation cycle should preserve a direct connection between evidence and delivery. The strategic noise map provides the starting point by identifying priority sources, areas, and exposed populations. Each priority problem can then be associated with a technically appropriate measure or package of measures, a lead authority, supporting institutions, a financing route, and a realistic implementation period. Monitoring should be defined at the same stage rather than added after implementation. Depending on the intervention, this may include an acoustic indicator, a process indicator, or both. The resulting record creates a traceable path from the initial exposure problem to the evidence used in the next revision of the action plan.

This cyclical approach also helps distinguish outputs from outcomes. Completing a road resurfacing project, installing a barrier, changing a traffic regime, or formally designating a quiet area is an implementation output. The corresponding outcome is the verified change in noise exposure, acoustic quality, or protection status. Recording both makes it possible to determine whether a measure was merely delivered or actually achieved its intended environmental objective. Where the expected effect is not achieved, monitoring results can support modification, replacement, or reprioritization of the measure in the subsequent planning cycle. In this way, the action plan becomes an adaptive management instrument rather than a static list of interventions.

5.2. Transferability to Other Serbian Agglomerations

A further implication concerns integration with other urban policies. Many effective noise measures are implemented through transport, road maintenance, public transport, mobility, spatial planning, and urban redevelopment rather than through stand-alone environmental projects [5]. Noise objectives should therefore be introduced early enough to influence these investment and planning decisions. In practice, this means that competent environmental authorities should not only prepare the Action Plan, but also establish a mechanism through which priority noise locations and acoustic objectives are communicated to the authorities responsible for transport, infrastructure, planning, and public utilities.

The proposed framework is transferable primarily at the level of process rather than at the level of individual measures. Other Serbian agglomerations can apply the same sequence of problem identification, measure

selection, assignment of responsibility, financing, monitoring, and review, while adapting the content of each step to local conditions. Source composition, urban morphology, traffic patterns, existing infrastructure, population distribution, and institutional capacity may differ substantially between agglomerations. Consequently, a measure that is technically and economically appropriate in Novi Sad should not be assumed to have the same priority elsewhere. The transferable element is the requirement that local choices are evidence-based, documented, and linked to implementation and verification.

A common process structure would also improve comparability between Serbian action plans without requiring identical local solutions. Consistent reporting of priority problems, responsible institutions, implementation status, expected and observed acoustic effects, and reasons for delays or revisions would make it easier to compare progress across planning cycles. It could also support the gradual accumulation of national experience on which measures are feasible under different urban conditions. Such comparability is particularly valuable while noise action planning in Serbia is still at an early stage and practical experience is limited.

For future plans, the level of specification should also be proportional to the importance and maturity of a measure. Measures that are ready for implementation can be described through a defined location, responsible authority, financing source, schedule, expected acoustic effect, and verification method. Measures that still require feasibility studies can be identified as preparatory actions, with a clear decision point and the information needed before implementation is approved. This distinction would reduce the risk of presenting conceptually attractive but insufficiently developed interventions as equivalent to measures for which delivery conditions are already known. It would also allow competent authorities to report progress more accurately, including preparatory work that is necessary before an acoustic benefit can be achieved.

The same logic can be applied to prioritization. Strategic maps identify areas of exposure, but a practical priority-setting procedure may also consider the number of people affected, the magnitude and persistence of the problem, sensitive land uses, technical feasibility, expected acoustic benefit, cost, planned infrastructure works, and the opportunity to combine noise reduction with other urban objectives. These factors need not be converted into a single numerical score. A transparent qualitative or multi-criteria procedure may be sufficient, provided that the reasons for assigning priority are documented. This would make decisions easier to explain during public consultation and easier to revisit when conditions, budgets, or strategic objectives change.

Public participation can also be linked more directly to the implementation cycle. Consultation is most useful when residents can see how comments relate to mapped problems, proposed measures, and subsequent decisions. Future Serbian action plans could therefore document not only that consultation occurred, but also the main issues raised, whether they were supported by acoustic or spatial evidence, and how they affected priorities or measure design. This approach would preserve the technical basis of strategic noise management while making the decision

process more transparent. Complaint and perception data could then serve as an additional information stream between formal planning cycles, helping authorities identify emerging local problems that may warrant targeted investigation [6].

Quiet-area management should form a parallel preventive component of this process. While mitigation addresses existing exposure, quiet-area policy can protect locations that already provide favourable acoustic conditions. Future Serbian action plans could therefore define a transparent procedure for candidate identification, acoustic and spatial assessment, formal designation, management objectives, and periodic review. Where data permit, public perception and accessibility can be used as additional information, particularly because the social value of a quiet urban space is not determined by sound level alone [6,7].

5.3. Practical Integration of Complementary Perspectives

The three complementary perspectives are most useful when they are connected to specific decisions in the action-planning process. Citizen perception and complaint information can support problem identification and help refine the spatial or temporal interpretation of mapped exposure. An equity perspective can be applied during prioritization to examine whether highly exposed or otherwise vulnerable groups are receiving proportionate attention and whether access to quiet areas and mitigation benefits is unevenly distributed [6,7]. The noise footprint, although not yet standardized, can be used conceptually when decisions have consequences that extend beyond a single source-receiver relationship, for example when transport, land-use, or infrastructure choices alter acoustic pressures across several parts of the urban system [8,9].

These perspectives should not be combined into a single composite indicator at the present stage. Their evidential bases, scales, and levels of methodological maturity differ, and the noise footprint in particular remains an evolving framework [9]. A more robust approach is to use them as separate questions within the planning process. For each priority area, authorities can ask whether measured or modelled exposure is consistent with reported community experience, whether the distribution of exposure and proposed benefits raises an equity concern, and whether the proposed intervention shifts acoustic impacts to another place, time period, or population group. This preserves methodological transparency while broadening the information considered in decision-making.

For Serbian agglomerations, progressive introduction is likely to be more practical than requiring all complementary data from the outset. Existing strategic maps and statutory indicators should remain the core evidence base. Complaint records and public-consultation information can be structured first because they may already exist within municipal systems. Where suitable demographic and spatial datasets are available, an equity screening can then be added to priority-setting. Noise-footprint analysis should initially remain exploratory and should be applied only where the planning question and available data justify it. This staged approach avoids

creating additional procedural burdens while allowing action plans to evolve as data quality, analytical capacity, and national experience improve.

Table 2 summarizes a proposed implementation framework derived from the Novi Sad evaluation and the literature reviewed in this study. It is not presented as a new legal requirement, but as a practical structure that could

improve consistency and traceability in future Serbian agglomeration action plans. The framework preserves the END-based acoustic assessment as its core while creating explicit links between evidence, measures, institutional delivery, financing, monitoring, and subsequent plan revision.

Table 2 Proposed implementation framework for future Serbian agglomeration noise action plans

Planning stage	Proposed implementation requirement	Purpose
1. Problem identification	Use strategic maps to identify priority sources, areas, exposed population, and quiet-area candidates.	Establish a documented evidence base for priorities.
2. Measure selection	Select source, path, transport/spatial-planning, or receiver measures appropriate to each problem [5].	Avoid generic measure lists and improve technical relevance.
3. Responsibility	Assign a lead authority and supporting institutions for each priority measure.	Create institutional ownership and inter-sectoral coordination.
4. Financing and scheduling	Identify financing mechanism, implementation phase, and target completion period.	Convert proposed measures into deliverable commitments.
5. Monitoring	Define baseline, acoustic or process indicator, and post-implementation verification.	Enable evaluation of effectiveness and revision of priorities.
6. Complementary assessment	Where appropriate, integrate perception/complaints, equity, and noise-footprint information [6–9].	Broaden evaluation beyond long-term strategic indicators.
7. Review and update	Report implementation status and feed monitoring results into the next planning cycle.	Support continuity, accountability, and adaptive management.

6. CONCLUSION

This study evaluated the 2025 draft Action Plan for Noise Protection for the Novi Sad Agglomeration as the first and, to date, the only noise action planning document prepared for an agglomeration in Serbia. The analysis combined the END and Serbian regulatory framework with contemporary European technical guidance and three complementary perspectives: citizen perception, environmental health equity, and the noise footprint concept.

The evaluation shows that the draft provides an important basis for the transition from strategic noise mapping to action planning, but the effectiveness of this transition will depend on how proposed measures are translated into implementation. Major measures should be linked to clearly identified noise problems and expected acoustic benefits, while responsibilities, financing, implementation schedules, and monitoring indicators should be defined in a traceable manner. Quiet-area protection would benefit from transparent designation and management criteria integrated with spatial planning.

Citizen perception and complaint data, environmental health equity, and the noise footprint framework are not requirements of the END, but they can complement conventional strategic indicators by adding information on community response, distribution of exposure and mitigation benefits, and the wider quality of the urban acoustic environment. The proposed implementation framework translates the lessons of the Novi Sad case into a sequence that links problem identification, measure selection, institutional responsibility, financing, monitoring, complementary assessment, and periodic review. Its application in future Serbian agglomerations could strengthen the operational character of noise action plans while preserving the END and national regulatory framework as their primary basis. Quantitative evaluation of implemented measures should follow when monitoring and implementation data become available.

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ENVIRONMENTAL NOISE MONITORING STRATEGIES FOR ESTIMATING ANNUAL NOISE INDICATORS: PRACTICES IN THE REPUBLIC OF SERBIA

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Abstract. *Annual environmental noise indicators require measurements or estimates representative of the full reference year, yet the monitoring strategies used by local authorities differ substantially. The availability of monitoring records was checked across 145 local self-government units in the study area; monitoring data were identified and analysed for 59 units (40.7%), primarily for 2023, with records from 2013–2024 used where necessary. Short-term mobile measurements using the 3+2 approach were reported for 42 of these 59 units (71.2%), whereas permanent monitoring was identified only in Niš. Indicator estimates were available for 597 sites in 55 units; approximately 80% of the sites were measured exclusively on weekdays. Among acoustically zoned sites with available results, exceedances occurred for 40.8% of daytime, 32.9% of evening and 57.8% of night-time values. The measured-cycle averages are estimates of annual indicators whose representativeness depends on the timing and duration of sampling. More systematic coverage of weekends, seasons and source conditions, together with explicit reporting of sampling limitations, would strengthen annual assessments and comparisons across municipalities.*

Key words: *Environmental noise, Noise monitoring strategy, Noise indicators, Acoustic zones, Local self-government, Republic of Serbia*

1. INTRODUCTION

Since the late 20th century, the intensive development of transport systems has caused a significant traffic noise problem in urban areas, along major roads and railways. The expansion of road traffic has been especially dynamic. Furthermore, the continuous rise in urban population density increases traffic volume and intensity, thereby driving up noise levels in urban areas [1].

Environmental noise is a significant public health concern in Europe, with road traffic the largest source of transport-noise exposure [2]. Reliable long-term indicators are needed to assess exposure, compare locations and guide noise-management measures [3,4].

The EU Environmental Noise Directive (2002/49/EC) [4] and Serbian noise legislation [5–12] provide a framework for assessing environmental noise, preparing strategic noise maps and action plans, and informing the public. In Serbia, monitoring data, strategic maps and

action plans are submitted to the Serbian Environmental Protection Agency (SEPA) [5].

To assess noise impacts and plan mitigation measures, the Republic of Serbia, the autonomous province, or the local self-government unit shall fund and implement noise monitoring within its territory [5]. This involves measuring noise levels and systematically tracking noise indicators to continuously evaluate environmental noise conditions. Noise indicators, limit values and calculation methods for noise indicators, and methods for assessing annoyance and harmful effects of environmental noise are defined by the Regulation [6]. Additionally, the SRPS ISO 1996-1 [11] and SRPS ISO 1996-2 [12] standards are established by the Regulation on noise measurement methods [7] as the mandatory baseline for measurement procedures and reporting scope. Noise monitoring is conducted by specialised, expert organisations authorised by the Ministry of Environmental Protection [5].

The current approach to determining environmental noise pollution levels involves two distinct noise monitoring strategies at a given location [3].

Short-term monitoring uses measurements taken during selected source-operating and meteorological conditions. Their use in estimating noise indicators over a longer period requires an appropriate sampling design and, where applicable, prediction or adjustment for conditions not measured. Mobile measurements are commonly repeated across reference periods and monitoring cycles [13,14].

Long-term monitoring uses extended measurement periods to capture more of the variability in source activity and sound propagation. It may be implemented through permanent or semi-permanent monitoring; the duration required for a representative annual estimate depends on the site and the purpose of assessment [3].

Permanent monitoring measures continuously at a fixed site and can directly characterise temporal variation across the monitored year when data coverage and quality are adequate. It can also support the calibration of strategic noise maps [13].

Semi-permanent monitoring uses relocatable equipment for continuous measurements over several days, weeks or months. Repeated periods selected across the year

can support estimation of annual indicators and reveal temporal trends, provided the sampling design accounts for unmeasured conditions [13].

When road traffic is the dominant noise source, traffic volume is measured during environmental noise monitoring to ensure data validity and enable accurate correlation analysis [12].

Permanent monitoring offers the most complete temporal coverage but requires substantial resources. Short-term mobile measurements cost less and may be useful for specific assessment tasks; their representativeness for annual indicators depends on the timing, number and duration of samples, source variability and meteorological conditions. Semi-permanent monitoring offers a practical option where continuous monitoring at every site is not feasible [14].

A study at the Faculty of Occupational Safety, University of Niš [1] evaluated a one-week measurement interval for urban sites dominated by road traffic of at least 1,000 vehicles per hour. Under the conditions examined, it reported an accuracy of 1.5 dB and precision of 1 dB for the estimated annual indicator. The selected week should avoid atypical events and holidays; locations with lower traffic volumes and greater temporal variability may require longer or repeated measurements, subject to site-specific verification [1].

These findings provide a basis for evaluating monitoring schedules at comparable high-traffic sites, rather than a universal duration applicable to every noise source and location [1].

The essential elements for calibrating strategic noise maps, the baseline document on environmental noise status, are the corresponding noise indicator values. Static strategic maps require equivalent noise levels for a given location spanning a full calendar year. Given the 24-hour variability of traffic noise, which is particularly pronounced between daytime and nighttime periods, and its impact on human activities during these times, monitoring at each location must provide annual data covering both the day-evening-night period (L_{den}) and the separate 8-hour night interval (L_{night}), as defined by Directive 2002/49/EC [4]. According to the Regulation [6], the 24-hour period is divided into three reference time intervals: *day* (lasting 12 hours, from 06:00 to 18:00), *evening* (lasting 4 hours, from 18:00 to 22:00), and *night* (lasting 8 hours, from 22:00 to 06:00). Thus, there are three corresponding noise indicators: L_{day} , $L_{evening}$ and L_{night} , representing the equivalent noise levels during the day, evening, and night periods, respectively. While strategic noise mapping utilises only L_{den} and L_{night} , acoustic spatial planning and the designation of quiet zones employ all four indicators, adding L_{day} and $L_{evening}$ to the assessment [3].

The annual day-evening-night noise indicator (L_{den}), which characterises noise annoyance over a one-year period, is defined in the Regulation [6] by the following equation:

$$L_{den} = 10 \log \left[\frac{1}{24} \left(12 \cdot 10^{\frac{L_{day}}{10}} + 4 \cdot 10^{\frac{L_{evening}+5}{10}} + 8 \cdot 10^{\frac{L_{night}+10}{10}} \right) \right] \quad (1)$$

where:

L_{day} – A-weighted long-term average noise level for all days throughout the year,

$L_{evening}$ – A-weighted long-term average noise level for all evenings throughout the year,

L_{night} – A-weighted long-term average noise level for all nights throughout the year.

Human perception of noise varies throughout the day; levels tolerated during daytime hours can severely disrupt evening relaxation and sleep at night. Consequently, the Environmental Noise Directive [4] introduces the composite indicator L_{den} (Day-Evening-Night), which represents the total 24-hour noise level by applying a +5 dB penalty to evening periods and a +10 dB penalty to night periods to protect human health and sleep quality.

The annual A-weighted long-term average sound levels in Eq. (1) are determined for specific reference time intervals over a one-year period using the following equations:

$$L_{day} = 10 \log \left[\frac{1}{N} \sum_{i=1}^N 10^{\frac{L_{day,i}}{10}} \right] \quad (2)$$

$$L_{evening} = 10 \log \left[\frac{1}{N} \sum_{i=1}^N 10^{\frac{L_{evening,i}}{10}} \right] \quad (3)$$

$$L_{night} = 10 \log \left[\frac{1}{N} \sum_{i=1}^N 10^{\frac{L_{night,i}}{10}} \right] \quad (4)$$

where:

i – the day number within the year,

N – the total number of days in a year.

In the preceding Eqs. (2), (3) and (4), the term "Year" refers to the reference year representing the timeframe for noise emissions and long-term average meteorological conditions.

Where population exposure and the relevant source-specific dose-effect relationships are available, L_{den} and L_{night} can also be used to estimate noise annoyance and sleep disturbance [6]. Such population estimates require an explicitly defined exposure population and calculation procedure.

SEPA environmental status reports for 2015–2024 [15] summarise reporting municipalities and noise indicators but do not systematically compare the monitoring strategies behind the reported values. The 2021 report for the Autonomous Province of Vojvodina [16] provides more detail on local monitoring arrangements. This study therefore examines the strategies used by Serbian municipalities and cities, the temporal and spatial coverage of their measurements, and the interpretation of indicator estimates derived from those measurements.

2. RESEARCH METHODOLOGY

This study examines environmental noise monitoring across urban areas in the Republic of Serbia, encompassing the City of Belgrade, 37 municipalities and 8 cities in the Autonomous Province of Vojvodina (APV), and 80 municipalities and 19 cities in Central Serbia (CS). In total, the research framework covers 117 municipalities and 28 cities. Four major cities (population >100,000) represent

the primary urban agglomerations: Belgrade, Novi Sad, Niš, and Kragujevac [15].

Most of the urban noise monitoring data for the Republic of Serbia relate to 2023 and were obtained from SEPA upon written request, covering 20 municipalities and cities in the Autonomous Province of Vojvodina and 18 in Central Serbia, including Belgrade.

To determine whether the remaining municipalities and cities conduct noise monitoring and to retrieve their respective data, this dataset was supplemented with information from local noise monitoring programs and environmental noise reports available on official municipal websites. Additional institutional data were sourced from the web portal of the Provincial Secretariat for Urbanism and Environmental Protection (PSUEP), from the Faculty

of Occupational Safety in Niš, and through a telephone survey conducted by the Institute of Public Health Kikinda (IPH Kikinda).

The analysis primarily uses 2023 data (50 municipalities and cities). Where 2023 data were unavailable, the latest accessible records from 2013–2024 were used (9 municipalities and cities). No monitoring data were located for 16 municipalities in AP Vojvodina and 70 in Central Serbia; this indicates a gap in the available records, but does not by itself establish that monitoring did not occur. For four municipalities, only 2023 monitoring programs, without results, were available.

A comprehensive overview of all analysed municipalities, their corresponding monitoring years, and specific data sources is systematized in Table 1.

Table 1 Status of environmental noise monitoring across local self-government units in Serbia (2013–2024)

Region	Monitoring year	Municipalities and cities included	Data source	Citation
APV	2023	Ada, Bačka Palanka, Bački Petrovac, Bеоčин, Bečej, Vršac, Indija, Kanjiža, Kikinda, Kovin, Kula, Nova Crnja, Novi Bečej, Novi Sad, Pančevo, Senta, Sombor, Sremska Mitrovica, Temerin, Čoka	SEPA (Official Request)	[SEPA, 2024]
APV	2023	Žitište, Zrenjanin, Subotica	Municipal Websites	[17,18,19]
APV	2023	Novi Sad, Subotica	PSUEP	[20]
APV	2013-2022	Bela Crkva (2022), Sečanj (2021), Ruma (2019), Pećinci (2013)	Municipal Websites	[21-24]
-	2023	Belgrade	SEPA (Official Request)	[SEPA, 2024]
CS	2023	Bajina Bašta, Bor, Valjevo, Vranje, Gornji Milanovac, Dimitrovgrad, Kladovo, Knjč, Lapovo, Leskovac, Negotin, Novi Pazar, Smederevo, Sokobanja, Trstenik, Šabac	SEPA (Official Request)	[SEPA, 2024]
CS	2023	Arandelovac, Kragujevac, Kruševac, Pirot, Požarevac, Čačak	Municipal Websites	[25-30]
CS	2024	Kraljevo	SEPA (Official Request)	[SEPA, 2024]
CS	2019-2020	Niš	Faculty Websites	[31]
CS	2013-2019	Osečina (2019), Lajkovac (2018), Vladičin Han (2013)	Municipal Websites	[32-34]
APV	2023 measurement strategy only	Novi Kneževac	Phone Survey (IPH Kikinda)	-
APV	2023 measurement strategy only	Odžaci	Municipal Websites	[35]
CS	2023 measurement strategy only	Zaječar, Surdulica	Municipal Websites	[36,37]

Note: APV – Autonomous Province of Vojvodina; SEPA – Serbian Environmental Protection Agency; PSUEP – Provincial Secretariat for Urbanism and Environmental Protection; CS – Central Serbia and IPH Kikinda – Institute of Public Health Kikinda.

Using a descriptive research approach, this study examined environmental noise monitoring in the Republic of Serbia.

For this descriptive comparison, practices were assessed against their ability to capture temporal variability: coverage of day, evening and night; inclusion of weekdays and weekends; duration and repetition of measurement cycles across the year; and availability of information on source activity and meteorological conditions. Permanent and multi-day or repeated semi-permanent measurements generally provide broader temporal coverage, but their representativeness for annual indicators must still be evaluated for each site. The available records do not permit a quantitative ranking of uncertainty across all strategies.

Monitoring reports and SEPA datasets generally presented results by measurement cycle (MC) at each monitoring site (MS). For descriptive comparison, measured-cycle levels were combined on an energy basis

separately for day, evening and night, using the form of Eqs. (2)–(4), and L_{den} was then calculated using Eq. (1). These results are referred to here as estimates of annual indicators derived from the available cycles. Equal weighting of measured cycles cannot reproduce a full-year average unless the cycles represent the relevant days and conditions, or suitable weights or corrections are applied. The source data did not consistently provide the information needed to quantify sampling uncertainty or to apply such corrections. Site-level processed data are reported in [38].

Acoustic-zone distribution was analysed only where zoning information was available. For those sites, available indicator estimates were compared with the applicable zone limits; the resulting compliance and exceedance percentages describe the analysed records and inherit the limitations of their sampling strategies. Indicator estimates were also grouped into level ranges for graphical presentation.

3. RESULTS OF THE RESEARCH AND DISCUSSION

Table 2 presents the collected environmental noise monitoring data from local self-government units in Serbia, categorised by the following qualitative

characteristics: monitoring strategy, individual measurement duration, number of annual measurement cycles (series), and the number of noise monitoring sites within each municipality or city.

Table 2 Environmental Noise Monitoring Strategies in Urban Areas of Serbia (2013–2024)

Monitoring strategy (individual measurement duration)	Region	Municipalities and cities
Short-term mobile (3+2) (10-15 min)	APV	MC = 1: Ada (3 MS), Bačka Palanka (23 MS), Beočin (10 MS), Kikinda (6 MS), Odžaci (3 MS), Ruma (5 MS), Subotica (City: 5 MS), Temerin (10 MS)
		MC = 2: Bačka Palanka (3 MS), Bečej (2 MS), Kikinda (19 MS), Subotica (City: 5 MS)
		MC = 4: Kanjiža (2 MS), Novi Kneževac (2 MS), Senta (3 MS), Čoka (2 MS)
		MC = 9: Pečinci (3 MS)
		MC = 10: Sremska Mitrovica (5 MS)
		MC = 11: Indija (4 MS)
Short-term mobile (3+2) (10-15 min)	CS	MC = 1: Arandelovac (5 MS), Bajina Bašta (22 MS), Bor (4 MS), Vladičin Han (10 MS), Gornji Milanovac (10 MS), Knić (6 MS), Kraljevo (40 MS), Lajkovac (5 MS), Lapovo (6 MS), Novi Pazar (13 MS), Požarevac (5 MS), Smederevo (12 MS), Sokobanja (2 MS), Surdulica (17 MS)
		MC = 2: Valjevo (12 MS), Dimitrovgrad (6 MS), Kladovo (3 MS), Negotin (6 MS), Požarevac (7 MS)
		MC = 3: Čačak (16 MS), Požarevac (6 MS)
		MC = 4: Kruševac (12 MS), Pirot (5 MS), Požarevac (2 MS), Sokobanja (2 MS), Trstenik (4 MS), Šabac (10 MS)
		MC = 5: Požarevac (3 MS)
		MC = 6: Požarevac (1 MS)
		MC = 11: Vranje (3 MS)
		MC = 12: Zaječar (7 MS), Kragujevac (6 MS)
Long-term semi-permanent (24 h)	APV	MC = 1: Bela Crkva (3 MS), Vršac (20 MS), Kovin (11 MS), Novi Bečej (2 MS), Sečanj (15 MS), Sombor (20 MS)
		MC = 2: Bački Petrovac (10 MS), Kovin (2 MS), Kula (8 MS), Nova Crnja (1 MS), Pančevo (33 MS)
		MC = 4: Kovin (2 MS), Pančevo (9 MS)
		MC = 6: Žitište (1 MS), Zrenjanin (13 MS)
		MC = 12: Novi Sad (City: 8 MS)
Long-term semi-permanent (24 h)		MC = 2: Belgrade (40 MS)
Long-term semi-permanent (24 h)	CS	MC = 1: Osečina (8 MS)
Long-term semi-permanent (72 h / 3 days)	APV	MC = 1: Sombor (8 MS)
Long-term semi-permanent (72 h / 3 days)	CS	MC = 2: Leskovac (6 MS)
Long-term semi-permanent (168 h / 7 days)	APV	MC = 2: Novi Sad (Province: 12 MS), Subotica (Province: 8 MS)
Long-term semi-permanent (168 h / 7 days)	CS	MC = 1: Osečina (1 MS)
Long-term permanent (24 h / 365 days)	CS	Niš (2 MS)

Note: APV – Autonomous Province of Vojvodina; CS – Central Serbia; MC = Annual Measurement Cycles; MS = Number of Monitoring Sites.

Environmental noise monitoring is conducted in 29 out of 45 municipalities and cities (64.4%) in AP Vojvodina and 29 out of 99 (29.3%) in Central Serbia. Including the City of Belgrade, monitoring covers 59 out of 145 Serbian municipalities (40.7%).

Short-term mobile (3+2) monitoring is the most commonly reported approach, listed for 42 of the 59 monitored municipalities (71.2%). Such limited-duration measurements may provide incomplete coverage for estimating annual indicators unless sampling is designed to represent temporal variation. Permanent monitoring was identified only in Niš (1/59, 1.7%); it was not identified in AP Vojvodina.

Multi-day semi-permanent monitoring was identified in five municipalities (8.5%). In Subotica and Novi Sad, the province organised two seven-day (168 h) cycles, in spring and autumn, providing coverage of both weekdays and weekends in two seasons. Sombor and Leskovac used three-day (72 h) measurements, and Osečina used a seven-day (168 h) measurement. Subotica also conducted local short-term mobile (3+2) monitoring. The degree to which each arrangement represents the year depends on the timing and conditions of its cycles.

In Sombor, Novi Sad, and Osečina, multi-day monitoring is supplemented by long-term semi-permanent monitoring with a 24-h individual measurement duration.

This strategy is also applied in Belgrade and 11 other municipalities in AP Vojvodina, totaling 15 monitored municipalities (25.4%).

Permanent or semi-permanent approaches were reported in 18 of the 59 monitored municipalities (30.5%). Because municipalities may use more than one strategy and measurement schedules differ, this count describes adoption of these approaches rather than a verified count of annual estimates meeting a common uncertainty criterion.

The spatial distribution of these monitoring strategies across Serbia's municipalities is illustrated using a thematic map, where different colors indicate specific noise monitoring approaches (Fig. 1).

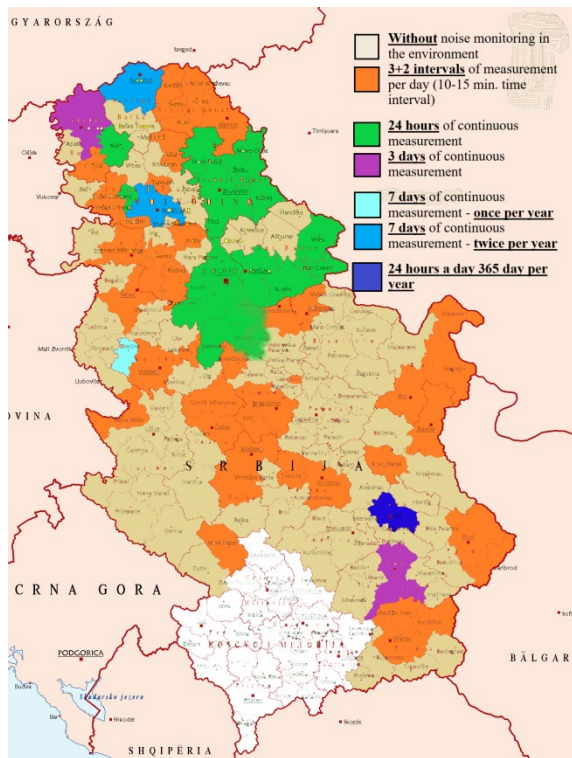


Fig. 1 Spatial distribution of environmental noise monitoring strategies across municipalities in Serbia (2013–2024)

A total of 626 environmental noise monitoring sites (MS) are established across the Republic of Serbia. Of these, 301 sites are located in the Autonomous Province of Vojvodina, 40 in the City of Belgrade, and 285 in Central Serbia, accounting for 48.1%, 6.4%, and 45.5% of the national total, respectively. The highest concentrations of monitoring sites are found in the cities of Pančevo (42), Belgrade (40), and Kraljevo (40).

Noise limits depend on acoustic-zone designation [6]. The distribution of monitoring sites across zones is therefore relevant to interpreting the available compliance results. Table 3 describes this distribution where zone information was reported; it does not establish whether the number of sites in each zone is proportional to the zone's area, population or exposure.

Acoustic-zone information was available for 268 of 626 monitoring sites (42.8%). Among these zoned sites, 53.4% were in Zone 5, while Zones 1–3 accounted for 33.9%. This indicates a concentration of the documented

zoned sites in Zone 5 and more limited observed coverage of noise-sensitive Zones 1–3. Whether these zones are underrepresented relative to monitoring needs cannot be established without a suitable reference distribution of land use, population and exposure. Improving the completeness of zoning metadata would support a more robust assessment.

Table 3 Distribution of measuring sites across acoustic zones and land-use types in accordance with the Regulation [6]

Acoustic Zone	AP Vojvodina [N]	City of Belgrade [N]	Central Serbia [N]	Republic of Serbia [N]	Republic of Serbia [%]
Zone 1	12	-	12	24	8.9
Zone 2	13	-	12	25	9.3
Zone 3	33	-	9	42	15.7
Zone 4	21	-	9	30	11.2
Zone 5	96	-	47	143	53.4
Zone 6	2	-	2	4	1.5
Total zoned sites [N]	177	-	91	268	-
Total monitoring sites [N]	301	40	285	626	-
Total zoned sites [%]	58.8	-	31.9	42.8	-

Note: Official data from SEPA did not include acoustic zone breakdown for the City of Belgrade.

For acoustically zoned sites with available measurements, the estimated day, evening and night values were compared with the corresponding zone limits. Table 4 reports the numbers and proportions of values above and within those limits. These comparisons should be interpreted in light of the temporal sampling limitations discussed above.

Table 4 Compliance and exceedance of available noise-indicator estimates at acoustically zoned monitoring sites

	L _{day}	L _{evening}	L _{night}
Total available assessed values	267	243	268
Compliant values	158	163	113
Compliant values [%]	59.2	67.1	42.2
Values exceeding the limit	109	80	155
Values exceeding the limit [%]	40.8	32.9	57.8

Note: Due to incomplete data, L_{day} is missing for one monitoring site, while L_{evening} data are missing for 25 monitoring sites.

Among the available zoned-site results, the proportion exceeding the applicable limit was highest at night (155/268, 57.8%), compared with 109/267 (40.8%) by day and 80/243 (32.9%) in the evening. The denominators differ because some period-specific data are missing. This pattern points to night-time noise as a priority for closer investigation at the sampled sites; it should not be interpreted as a population exposure rate or a nationally representative exceedance rate.

Noise-indicator estimates were processed for 597 monitoring sites in 55 municipalities and cities (37.9% of the 145 units) and are presented by level range in Figs. 2–5.

Because period-specific data were missing at some sites, 596 daytime, 566 evening and 597 night-time

estimates were available; 566 complete sets could be used to calculate L_{den} estimates.

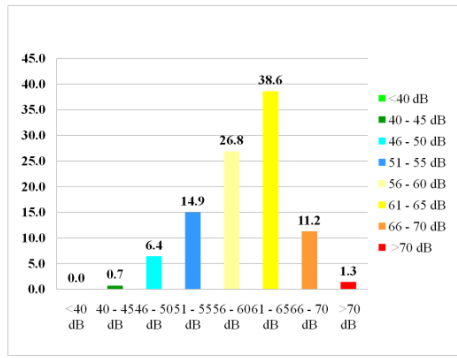


Fig. 2 Percentage [%] distribution of daytime noise indicators L_{day} by noise-level range in the Republic of Serbia

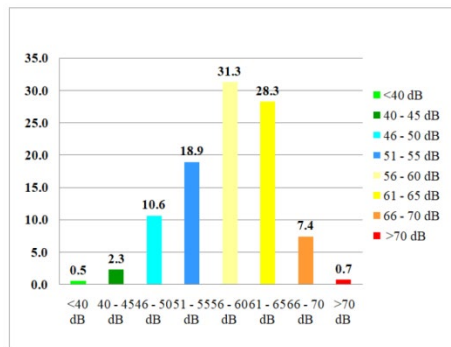


Fig. 3 Percentage [%] distribution of evening noise indicators $L_{evening}$ by noise-level range in the Republic of Serbia

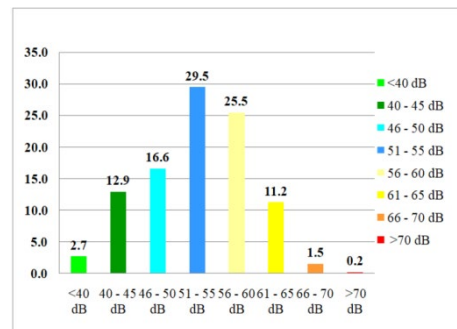


Fig. 4 Percentage [%] distribution of night noise indicators L_{night} by noise-level range in the Republic of Serbia

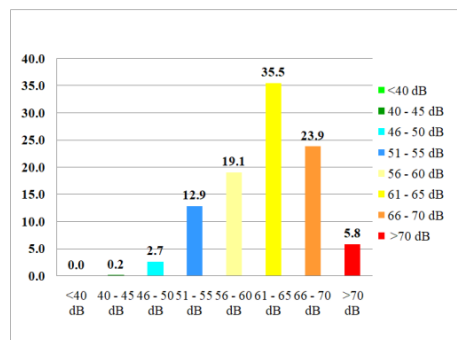


Fig. 5 Percentage [%] distribution of day-evening-night noise indicators L_{den} by noise-level range in the Republic of Serbia

Regarding the monitoring dynamics, noise assessment was conducted exclusively on weekdays at the majority of sites: 475 sites for L_{day} (79.7%), 450 for $L_{evening}$ (79.5%), and 475 for L_{night} (79.6%). Monitoring encompassed both weekdays and weekends at 79 sites across all three indicators (13.2% for daytime/night-time and 14.0% for evening). Conversely, weekend-only monitoring was limited to 7 sites (1.2%) for L_{day} , 2 sites (0.4%) for $L_{evening}$, and 8 sites (1.3%) for L_{night} . Finally, sampling period metadata were unavailable for 35 sites across all indicators (5.9% for daytime/night-time and 6.2% for evening).

L_{den} is defined as a long-term average over a reference year [6]. Sampling both weekdays and weekends is relevant because source activity can vary by day of the week. Approximately 80% of the sites with these indicator estimates were monitored only on weekdays, so the unmeasured weekend conditions may bias an annual estimate in either direction depending on the site. The magnitude of this possible bias cannot be determined from the available records. Future monitoring programs should record the sampling calendar and the rationale for its representativeness.

Across the 597 analysed sites, the most common ranges of the available estimates were 61–65 dB for L_{day} and L_{den} , 56–60 dB for $L_{evening}$ and 51–55 dB for L_{night} ; values above 70 dB occurred in at most 6% of the reported site estimates. These are distributions across monitored sites, not population exposure distributions. Annoyance percentages cannot be interpreted from these site-level data without a defined exposed population, source attribution and a documented dose–effect calculation.

4. CONCLUSION

The review identified monitoring data in 59 of 145 local self-government units and a strong reliance on short-term mobile (3+2) measurements. Estimates derived from these cycles should be reported with their sampling schedules and limitations. Among the analysed sites, approximately 80% had weekday-only measurements, while zoning information was available for only 42.8% of all 626 monitoring sites. Improving temporal coverage and metadata would make comparisons of annual noise indicators more defensible.

Three practical priorities follow from these findings:

- Temporal coverage: Include weekends and relevant seasonal conditions in the sampling design. Consider repeated multi-day measurements where site-specific evidence supports their representativeness; the one-week result reported in [1] applies to the high-traffic conditions studied.
- Spatial documentation: Record acoustic-zone designation for each site and review the coverage of noise-sensitive areas against land use, population and exposure before changing the network.

- Site-specific duration: At locations with greater temporal variability, evaluate whether longer or additional monitoring periods are needed to estimate annual indicators with an acceptable uncertainty.

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EXPLAINABLE MACHINE LEARNING FOR ENVIRONMENTAL NOISE ASSESSMENT IN URBAN AREAS

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Abstract. Road traffic noise is a major environmental concern, while continuous monitoring is often limited by resource requirements. This study evaluates machine learning for equivalent noise level (L_{eq}) predictions using long-term monitoring data and spatial characteristics of measurement sites. A dataset of 5,763 L_{eq} values from 15 locations in Niš, Serbia, was analysed using Linear Regression, Random Forest, and Extreme Gradient Boosting. Extreme Gradient Boosting achieved the lowest mean absolute error (MAE = 0.742 dB), although its overall advantage over a baseline model was limited. Shapley additive explanations showed that spatial characteristics had the strongest influence on model predictions and indicated possible dependencies among spatial predictors. The results suggest that machine learning can complement conventional noise monitoring by estimating L_{eq} during unmeasured periods at previously monitored locations, while its application to unseen locations requires further validation.

Key words: Environmental noise monitoring, Road traffic noise, Machine learning, Shapley additive explanations

1. INTRODUCTION

Environmental noise represents a major public health concern. Road traffic is the dominant source, especially in densely populated urban areas. Approximately 112 million people in Europe are exposed to long-term transport noise levels above the Environmental Noise Directive thresholds (Directive 2002/49/EC) [1]. Long-term exposure to noise is associated with sleep disturbance, stress, cardiovascular and metabolic diseases, mental health effects, and premature mortality. In 2021, long-term exposure to transport noise was associated with an estimated 73,000 premature deaths, 49,000 new cases of cardiovascular disease, and 23,000 new cases of type 2 diabetes [2,3]. To address this issue systematically, Directive 2002/49/EC (END) requires the preparation of strategic noise maps and action plans for agglomerations, major roads, railways, and airports [1]. The development of strategic noise maps requires reliable methods for estimating noise levels over large areas, including locations and time periods not covered by continuous monitoring. In the European regulatory framework, and consequently in Serbia, strategic noise mapping is based on the CNOSSOS-EU methodology, which provides common methods for the assessment of road, railway, aircraft and industrial noise.

CNOSSOS-EU was also applied in the development of the strategic noise maps for the city of Niš [4]. Different methodologies of road traffic noise prediction rely on different sets of input data and specific assumptions regarding traffic flow, vehicle construction and speed, road geometry, meteorological conditions, temporal, and spatial features. Their accuracy may decrease in complex urban environments or when detailed input data are unavailable [5]. Although continuous noise monitoring provides reliable data, it is time-consuming and often limited due to the high costs of installing and maintaining fixed monitoring stations across an urban area. Previous studies conducted in Niš have addressed the practical limitations of environmental noise monitoring. Prašćević et al. highlighted the importance of long-term monitoring and systematic noise databases [6], while Mihajlov et al. compared permanent and semi-permanent road traffic noise monitoring approaches [7]. Noise monitoring is often feasible only at selected locations and during specific time periods, resulting in gaps in the spatial and temporal coverage of measurement data. These limitations highlight the need for methods that can estimate noise levels when continuous noise monitoring is not available. More recent studies investigated strategies for determination of the optimal measurement time interval [8] and identified the season, month and day of the week that are representative of the application of noise monitoring in terms of the smallest deviations from the annual values of noise indicators [9]. Following previous research on noise monitoring optimisation by reducing the need for continuous measurements, this study evaluates the ability of machine learning (ML) models to accurately predict noise levels at a known location based on available long-term monitoring data and relevant spatial and time-related characteristics. Reliable noise prediction is essential for effective urban and transport planning. It helps to identify areas with higher noise exposure and design appropriate noise reduction strategies. ML applications in urban traffic noise estimations are based on different predictors (traffic flow, vehicle construction, road classification, meteorological variables, spatial, and temporal features). Tree-based ensemble methods, such as Random Forest (RF) and Extreme Gradient Boosting (XGBoost), as well as neural network (NN) and deep learning (DL) models,

have been successfully applied to environmental noise prediction [10-13]. Recent studies have also explored the prediction of future noise levels using historical measurement data. Different ML and DL approaches, including Long Short-Term Memory (LSTM), Gated Recurrent Unit (GRU), gradient-boosting, and hybrid models, have been applied to short- and long-term noise prediction [14-16]. The increasing complexity of ML models can reduce the transparency of their predictions, encouraging the use of explainable artificial intelligence (XAI) methods to better understand model behaviour, such as SHAP (SHapley Additive exPlanations) [17] and LIME (Local Interpretable Model-Agnostic Explanations) [18]. SHAP provides a quantitative measure of how individual traffic, spatial, and urban characteristics contribute to noise level predictions [10,12,13].

The aim of this research is to evaluate the potential of ML for estimating equivalent noise levels L_{eq} using available data from long-term (annual) noise monitoring and the spatial characteristics of the measurement locations. Spatial characteristics of the measuring locations, including distances to roads, buildings, industrial areas, and parks, were derived from OpenStreetMap (OSM) [19]. The contribution of this study is twofold. It evaluates whether OSM-derived spatial characteristics combined with cyclical temporal predictors can support temporal L_{eq} estimation at previously monitored urban locations and assesses predictions by Linear Regression, RF and XGBoost models relative to a baseline model. SHAP analysis is used to identify the predictors that strongly influence the ML noise level predictions.

2. METHODS

2.1. Noise measurements and study areas

This study uses data obtained from long-term road traffic noise monitoring conducted by the Noise and Vibration Laboratory of the Faculty of Occupational Safety in Niš [7,9]. Measurements were performed using the Brüel & Kjær Environmental Noise Management System (ENMS), consisting of Type 7843 software, two Type 3636-B-203 noise monitoring terminals, and a Vaisala WXT520 meteorological station [8,9]. The meteorological station simultaneously recorded air temperature, relative humidity, atmospheric pressure, wind speed and direction, and precipitation [8]. The microphones were positioned at a height of 4 m above ground level, and the measurements were carried out in accordance with the SRPS ISO 1996-2 standard [9]. Since the monitoring terminals were relocated between measurement sites, each location was monitored for a limited period of approximately one year. Measurements at 14 locations were conducted between 2014 and 2022, primarily along major roads where road traffic was the dominant noise source [9]. The dataset was supplemented with additional measurements performed in 2024 and 2025, resulting in a total of 5,763 L_{eq} observations from 15 monitoring locations. According to [9], the selected measurement locations had comparable traffic conditions, including continuous mixed traffic flow and flat road geometry, with reported traffic volumes indicating relatively stable traffic conditions across the selected sites.

Figure 1 shows the spatial distribution of the monitoring locations across the urban area of Niš. The locations represent different urban environments, including residential, institutional, traffic-dominated, industrial, and mixed-use areas.

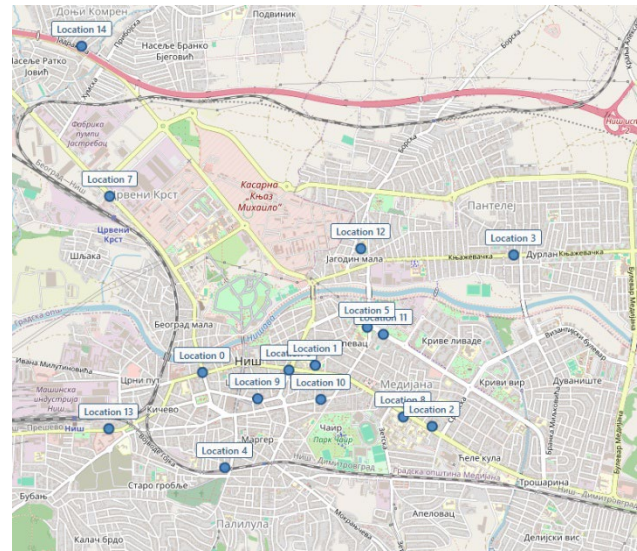


Fig. 1 The spatial distribution of the measurement locations across the urban area of Niš. Measuring locations cover different urban sites, including residential, institutional, traffic-dominated, industrial, and mixed urban areas.

2.2. Predictor Variables and Training-Test Dataset Formation

Spatial predictors for the measurement locations were derived from OpenStreetMap (OSM) data [19]. For each location, spatial features define distance to the road network, buildings, industrial areas, and parks. The initial set of spatial predictors included distance-based variables and characteristics derived from spatial buffers of different radii. Because several predictors were highly correlated and contained similar spatial information, the set was reduced to avoid redundancy. The final set of spatial features includes distance to the nearest road, distance to the main road, distance to the nearest building, distance to an industrial area, distance to a park, total road length within 100 and 500 m buffers, number of buildings within 100 and 500 m buffers, percentage of industrial area within 100 and 500 m buffers, and percentage of park area within 100 and 500 m buffers. Spatial predictors are constant for each measurement location. In addition to the spatial predictors, temporal predictors were derived from the long-term noise monitoring to represent periodic variations over the week and the year. Cyclical transformations of the day of year and day of week were used. Such a representation helps to avoid artificial discontinuities between the end and the beginning of a cycle, such as between the last and first day of the year (or between Sunday and Monday).

To account for the temporal structure of the data, the training and test sets were defined using a chronological rather than a random split. For each sufficiently long time series, observations were sorted chronologically, with the first 80 % used for model training and the remaining 20 % reserved for testing. Data from

each monitoring location were divided into separate time series whenever a gap of 30 days or more occurred between consecutive measurements. Time series containing fewer than 30 observations were excluded from the evaluation to ensure a sufficiently reliable training/test split. A 30-day gap was adopted as a practical threshold for identifying discontinuities in the monitoring records. Longer gaps may correspond to changes in seasonal, traffic-related, or other time-dependent conditions, making it less appropriate to treat measurements as a single continuous time series. Accordingly, model performance was evaluated in terms of temporal prediction at previously observed locations rather than spatial generalisation to unseen locations.

2.3. Machine learning models and SHAP Analysis

Three ML algorithms were applied to predict L_{eq} values: LR, RF, and XGBoost [20,21].

Linear Regression (LR) was used as the basic linear model. The input features were standardised using StandardScaler prior to fitting the regression model. Although LR cannot fully capture the nonlinear relationships that may characterise urban noise patterns, it provides a useful benchmark for comparison with more flexible ML models [20].

Random Forest (RF) is an ensemble learning method that combines predictions from multiple decision trees to improve predictive performance and reduce model variance [20]. The RF model consisted of 300 decision trees, with a maximum tree depth of 5 and a minimum of 5 samples per leaf. A fixed random seed was used to ensure reproducibility.

XGBoost is a gradient-boosting method in which decision trees are built sequentially, with each additional tree aiming to reduce the remaining prediction error by optimising the loss function. Regularisation and controlled tree complexity help limit overfitting and improve model generalisation [21]. The XGBoost model was implemented using a squared-error regression objective. The final configuration included 300 estimators, a maximum tree depth of 3, a learning rate of 0.03, a minimum child weight of 5, a subsample ratio of 0.8, and a column subsampling ratio of 0.8. The L1 and L2 regularisation parameters were set to 0.1 and 1.0, respectively. Hyperparameter tuning for all ML algorithms was performed on the training data to identify model configurations that provided the best predictive performance while limiting overfitting.

In addition to the machine learning models, a simple reference model (baseline) was used for comparison. For each time series, the baseline predicted the mean L_{eq} value of the corresponding training subset for all observations in the test subset. This provided a reference for assessing whether the more complex models achieved improved predictive performance compared with a simple estimate of the typical noise level within each time series. The models were evaluated using two predictor configurations: spatial predictors only and a combination of spatial and temporal predictors.

Model performance was evaluated using mean absolute error (MAE), root mean squared error (RMSE), and the coefficient of determination (R^2). MAE represents the average magnitude of prediction errors in dB, while RMSE is more sensitive to occasional large deviations.

The XGBoost model was interpreted using SHAP to quantify the contribution of individual predictors at both global and local levels. Global SHAP analysis identified the spatial and temporal predictors with the strongest influence on model predictions, while local analysis was applied to the observation with the largest absolute prediction error (difference between the predicted and measured L_{eq} value). The SHAP results were used to explain how individual features contributed to the model predictions, but these contributions should not be interpreted as proof that the features directly cause changes in noise levels.

3. RESULTS

3.1. Predictive Performance of Machine Learning Models

The analysed dataset included 5,763 values of L_{eq} from 15 monitoring locations in Niš.

Values of L_{eq} varied substantially across locations, from approximately 58.7 to 71.4 dB, reflecting differences in the local acoustic environment. In contrast, day-to-day variation within individual locations was generally smaller than the variation between locations. This pattern indicates that location-specific characteristics provide important information about the typical noise level and therefore play an important role in model prediction. The results of the applied ML models are presented in Table 1.

Table 1 Performance of different models in predicting L_{eq}

Model	Predictors	MAE [dB]	RMSE [dB]	R^2
Baseline	Series-specific training mean	0.757	1.070	0.928
Linear Regression	Spatial features	1.884	2.430	0.630
Linear Regression	Spatial and temporal features	1.849	2.368	0.649
Random Forest	Spatial features	0.825	1.178	0.913
Random Forest	Spatial and temporal features	0.828	1.193	0.911
XGBoost	Spatial features	0.837	1.187	0.912
XGBoost	Spatial and temporal features	0.742	1.110	0.923

Table 1 shows a comparison between the linear model and the tree-based ensemble methods. A baseline was used as a simple reference model. For each time series, the baseline predicted the mean L_{eq} value of the training subset for all observations in the corresponding test subset. Because this baseline is calculated separately for each series, it already reflects the typical noise level of the observed location. MAE and RMSE are reported to three decimal places to facilitate comparison between models, although such small differences should not necessarily be interpreted as physically significant. LR showed the weakest predictive performance, indicating that the relationship between the selected predictors and L_{eq} was not adequately represented by a simple linear model. RF substantially reduced prediction errors, although the addition of temporal predictors slightly worsened performance. For XGBoost, the inclusion of temporal

predictors reduced MAE from 0.837 to 0.742 dB, corresponding to an approximately 11.4 % reduction in MAE relative to the spatial-only configuration. Nevertheless, the best XGBoost model only slightly improved MAE compared with the baseline (0.742 vs. 0.757 dB), while the baseline retained a lower $RMSE$ and slightly higher R^2 . These results suggest that temporal predictors provided additional information for XGBoost, but the advantage of the more complex model over the series-specific baseline remained limited. XGBoost was able to exploit the temporal information more effectively. The improvement after adding temporal predictors shows that the model also captures time-related variations, although spatial characteristics still have the strongest influence on the predictions.

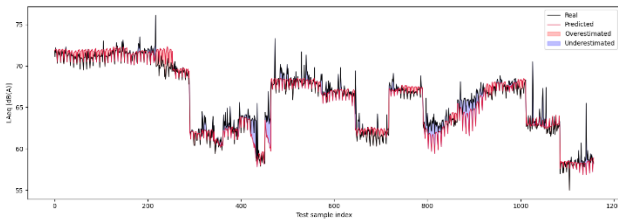


Fig. 2 Comparison of measured and predicted L_{eq} values using the XGBoost model

A comparison of measured and predicted L_{eq} values using the XGBoost model is shown in Fig. 2. It represents an evaluation of L_{eq} predictions using a combination of spatial and temporal features. Red shaded regions indicate cases in which the model overestimates the measured value, while blue shaded regions indicate underestimation. Prediction errors are relatively small in most cases, on the order of 1 dB, except for several isolated peaks and segments with more pronounced deviations. The largest errors are predominantly associated with underestimation; in fact, all ten largest errors correspond to cases in which the predicted noise level was lower than the measured value. A particularly notable case occurred on 14 September 2025, when the same higher L_{eq} value of 65.5 dB was measured at two different locations. For the first location, the model predicted 56.9 dB, corresponding to an underestimation of 8.6 dB, while for the second location it predicted 57.8 dB, corresponding to an underestimation of 7.7 dB. The results obtained also suggest that further improvements may require the inclusion of additional relevant predictors, together with a larger training dataset and a greater number of monitoring locations.

3.2. SHAP analysis

SHAP is particularly useful for complex ML models because it improves model interpretability by showing how individual features influence predictions [17]. The SHAP method was applied for a more detailed interpretation of the XGBoost model (Fig. 3). To provide a global interpretation of the XGBoost model, a SHAP summary plot was used to visualise both the magnitude and direction of individual feature contributions across all predictions. Features are ranked according to their overall importance, while the distribution of SHAP values shows whether

different feature values tend to increase or decrease the model predictions.

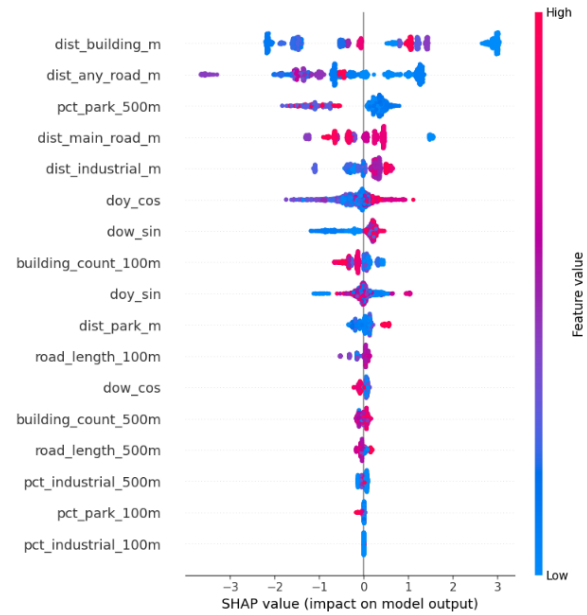


Fig. 3 SHAP summary plot

The x-axis represents the SHAP value, i.e., the contribution of each predictor to the model's output relative to the model's expected value. Since the model predicts L_{eq} directly in dB, SHAP values are expressed in the same units. The colour indicates the predictor's value, from low (blue) to high (red), while predictors are ordered according to their mean absolute SHAP value, i.e., the mean absolute magnitude of a predictor's contribution to the model predictions. The five predictors with the highest mean absolute SHAP values in the fitted XGBoost model were spatial characteristics, with distance to the nearest building (*dist_building_m*) showing the largest SHAP contribution, ranging approximately from -2 to +3 dB. The SHAP summary plot indicates that spatial characteristics dominate the model's predictions, with distance to the nearest building (*dist_building_m*) and distance to the nearest road (*dist_any_road_m*) showing the highest mean absolute SHAP value and a possible complex, non-monotonic relationship. This may reflect interactions with other predictors. Higher values of the percentage of park area within a 500 m buffer (*pct_park_500m*) and distance to the main road (*dist_main_road_m*) were generally associated with negative SHAP contributions. The pattern for distance to the nearest industrial area (*dist_industrial_m*) was less intuitive. This pattern suggests that its contribution to the model predictions should not be interpreted independently. The SHAP dependence plot for *dist_building_m* shows a considerable spread of SHAP values for similar feature values, indicating that its effect on predicted noise levels is not uniform. This suggests that the influence of the distance to the nearest building may depend on other spatial characteristics included in the model, pointing to possible interactions between predictors. Several spatial predictors exhibit complex and non-monotonic SHAP patterns, indicating that their effects on the model output should not be interpreted independently or as evidence of a causal

effect. Further analysis should be performed to assess dependence and potential multicollinearity among the predictors. Due to potential interdependence among some spatial predictors, these results should be interpreted as reflecting the model's predictive behaviour rather than as evidence of causal relationships. The temporal predictors *doy_sin* and *doy_cos* encode the position within the annual cycle, whereas *dow_sin* and *dow_cos* encode the position within the weekly cycle. These cyclical transformations avoid artificial discontinuities between the end and beginning of the respective cycles. Thus, the SHAP values indicate how the encoded annual and weekly position of a given date shifts the model prediction. Temporal predictors had smaller but still noticeable contributions, with SHAP values generally within approximately ± 1 dB, although *doy_cos* reached larger negative contributions of around -1.5 dB. The specific season and day of the week associated with the temporal SHAP contributions can be identified from the original date and the cyclical encoding of *doy_sin/doy_cos* and *dow_sin/dow_cos*.

Fig. 4 shows the dependence of the SHAP values for *dist_building_m* on the distance to the nearest building, while point colour represents the distance to the nearest road (*dist_any_road_m*). A short distance to the nearest road does not correspond to a consistently positive or negative SHAP contribution. Instead, similar road-distance values are associated with different SHAP values depending on the distance to the nearest building.

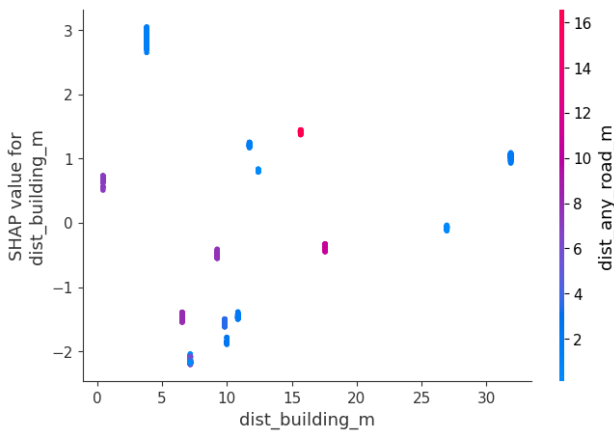


Fig. 4 The SHAP dependence plot shows how distance to the nearest building (*dist_building_m*) influences the predicted noise level, with colour indicating the distance to the nearest road (*dist_any_road_m*).

The SHAP dependence plot for *dist_building_m* shows a non-linear relationship between the distance to the nearest building and its contribution to the predicted noise level. Similar ranges of *dist_building_m* are associated with markedly different SHAP values, indicating that its effect is not uniform across observations. The colour pattern suggests a possible interaction between *dist_building_m* and *dist_any_road_m*; however, the dependence plot alone does not establish or quantify this interaction.

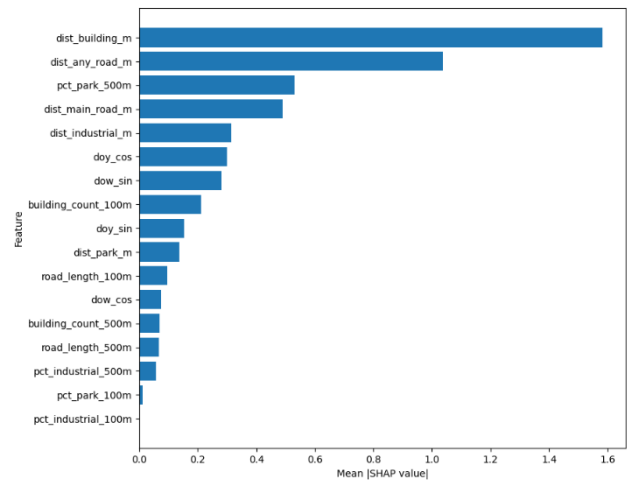


Fig. 5 The mean |SHAP| plot. Each value represents the average magnitude of a feature's contribution to the model predictions

In contrast to the SHAP summary plot (Fig. 3), the mean |SHAP| plot (Fig. 5) shows only the overall importance of each feature, without indicating the direction or distribution of its contribution across individual predictions. The mean absolute SHAP value represents the average magnitude of a feature's contribution to the model predictions, regardless of whether the contribution is positive or negative. Higher values therefore indicate greater overall importance.

Among the considered features, the predictor distance to the nearest building (*dist_building_m*) had the largest mean |SHAP| value.

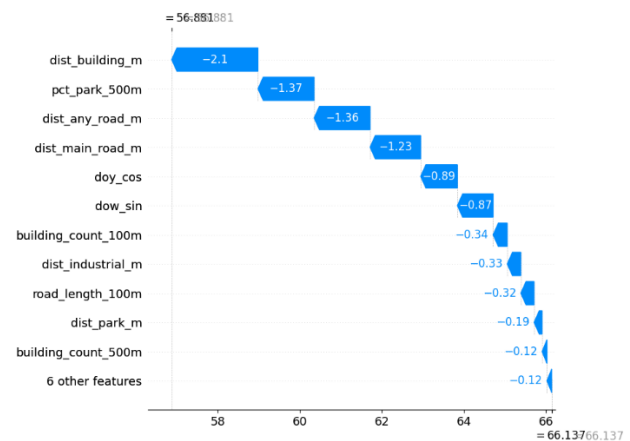


Fig. 6 SHAP waterfall plot for the observation with the largest absolute prediction error (location 14, 14 September 2025)

The SHAP waterfall plot (Fig. 6) explains a single model prediction by showing how each feature shifts the prediction from the model's expected value toward the final predicted value. Positive contributions increase the prediction, while negative contributions decrease it. The observation with the largest absolute prediction error was analysed in detail. At measurement location 14 on 14 September 2025, the equivalent noise level (L_{eq}) was 65.5 dB, whereas the XGBoost model predicted 56.9 dB, resulting in an underestimation of 8.6 dB. However, the

reference point is not the measured L_{eq} value, but the model's base value (66.14 dB), representing the expected model output before the feature values of the specific observation are considered. The local SHAP analysis showed that several features contributed negatively to the model output, shifting the prediction below the base value. The largest negative contributions were associated with the distance to the nearest building (*dist_building_m*), the percentage of park area within a 500 m radius (*pct_park_500m*), the distance to the nearest road (*dist_any_road_m*), and the distance to the main road (*dist_main_road_m*). For this prediction, the cyclical temporal features also contributed negatively, with *doy_cos* and *dow_sin* decreasing the model output by approximately 0.89 dB and 0.87 dB, respectively. These values represent contributions of the encoded annual and weekly cycles and should not be interpreted independently as direct effects of a specific season or day of the week.

4. DISCUSSION

The results show that, when continuous monitoring is not available, L_{eq} values at known monitoring locations can still be estimated with low average error. The achieved prediction accuracy is comparable to values reported in previous studies of ML applications [5,15], although direct comparison is limited by differences in datasets, predictor sets, target variables, and validation procedures. A key finding is that the baseline achieved an *MAE* very close to that of the best ML configuration, while yielding a slightly lower *RMSE* and a slightly higher R^2 . This indicates that a substantial part of the observed predictive performance is related to stable differences in typical noise levels between monitoring locations. A high R^2 at known locations does not mean that the model will work equally well at new locations. Since the spatial features are fixed for each site, the model may partly learn the differences between locations. Consequently, their predictive value should not be interpreted as evidence that individual spatial characteristics directly determine noise levels. Their ability to generalise spatially can only be properly assessed using monitoring locations that were not represented during model training. The results suggest that temporal features provide additional predictive information, particularly for XGBoost, although their contribution was smaller than that of the spatial characteristics. Among the evaluated ML models, XGBoost with spatial and temporal predictors achieved the lowest *MAE* (0.742 dB; *RMSE* = 1.110 dB, R^2 = 0.923). The inclusion of temporal predictors reduced XGBoost *MAE* by approximately 11.4% relative to its spatial-only configuration. The largest prediction errors were underestimations, indicating that static OSM data combined with cyclical temporal information were insufficient to capture some atypically high noise levels. This directly supports the need for dynamic predictors. SHAP analysis helps explain how the model forms its predictions, while also showing that spatial predictors should not be interpreted as causal effects. The SHAP analysis further showed that spatial characteristics dominated the overall model predictions, while temporal features had smaller but still noticeable contributions. More generally, SHAP values describe the behaviour of the

fitted model and should not be interpreted as evidence of causal relationships between individual predictors and measured noise levels. Analysis of prediction errors revealed an additional limitation of the model. All ten largest errors corresponded to underestimations of measured noise levels. A particularly pronounced case occurred on 14 September 2025, when the model underestimated the measured L_{eq} at two locations by approximately 7.7 and 8.6 dB. The local SHAP analysis showed that several spatial and temporal features simultaneously shifted the model output downward. However, these SHAP contributions explain how the model arrived at its prediction rather than why the measured noise level was unusually high. The occurrence of large errors at two locations on the same day may indicate that one or more acoustic factors not represented by the available predictors, such as traffic conditions, meteorology, or atypical local activities, were present on that day.

The main limitations of this research are the relatively small number of monitoring locations, the evaluation restricted to locations already represented in the training data, and the use of predominantly static spatial characteristics together with temporal predictors. Correlations and possible dependencies among spatial predictors complicate the interpretation of individual SHAP contributions and should be investigated further using correlation analysis or other feature-redundancy diagnostics. If significant spatial dependency and correlation are detected, the model could be further improved by introducing additional spatial predictors. In addition, rather than providing only a single predicted value, it would be useful to estimate prediction uncertainty intervals, which could help to identify larger deviations in noise levels [22]. Combining noise monitoring during representative periods [9] with ML-based prediction could improve monitoring efficiency while reducing measurement costs and the need for continuous field measurements. The relatively small dataset may limit the study's ability to capture short-term variations in traffic and meteorological conditions. In addition, the models were not yet validated on completely unseen locations, which limits conclusions about their spatial generalisability. Future work should include validation at unseen monitoring locations, the use of larger and more recent datasets, the inclusion of dynamic traffic and meteorological variables, uncertainty analysis, and separate modelling of L_{day} , $L_{evening}$, and L_{night} indicators.

5. CONCLUSION

The results show that L_{eq} at previously monitored locations can be estimated with low average error using spatial and temporal information. Among the evaluated ML models, XGBoost using both spatial and temporal predictors achieved the lowest *MAE* (0.742 dB). However, the baseline achieved a slightly lower *RMSE* and a slightly higher R^2 , indicating that a substantial part of the predictive performance is attributable to stable differences in typical noise levels among locations. The inclusion of temporal predictors reduced the *MAE* of XGBoost by approximately 11.4 % relative to the spatial-only configuration.

This shows that temporal information helps the model capture changes in noise levels over time, in addition to the differences between monitoring locations. SHAP analysis showed that the fitted model relied predominantly on spatial characteristics, whereas temporal predictors had smaller but still noticeable contributions. These SHAP results describe the predictive behaviour of the fitted model and should not be interpreted as evidence of causal relationships between individual spatial characteristics and measured noise levels. The largest prediction errors were associated with underestimation of atypically high measured noise levels, suggesting that additional dynamic information, particularly traffic and meteorological variables, may be required to reliably represent short-term deviations from typical noise levels. ML-based prediction may therefore complement conventional monitoring by estimating L_{eq} during periods without monitoring data at previously monitored locations. However, validation at an entirely unseen monitoring location is required before conclusions regarding spatial generalisability can be drawn. Future work should include additional monitoring locations, dynamic traffic and meteorological predictors, uncertainty estimation, and spatially independent validation.

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IMPACT OF APPROACH PROCEDURES ON NOISE EXPOSURE AROUND BELGRADE AIRPORT

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Abstract. Aircraft noise is a major environmental concern in areas surrounding airports, where frequent aircraft operations can affect nearby communities. At Belgrade Nikola Tesla Airport, aircraft noise is particularly relevant due to the volume of air traffic and the proximity of residential areas to aircraft flight paths. This study aimed to assess how different approach procedures affect the spatial distribution of aircraft noise and the areas enclosed by selected noise contours. The EUROCONTROL IMPACT software was used to model four scenarios for an Airbus A319: a conventional approach, Continuous Descent Operations (CDO), a steeper approach with a 4.5° descent angle, and the Multiple Aiming Points (MAP) concept, involving a 1,500 m displacement of the aiming point from its standard position. The assessment was based on Sound Exposure Level (SEL) and maximum A-weighted sound level (LA_{max}), with noise contours and their areas analysed using QGIS. The results showed that the steeper approach produced the smallest contour areas among the four scenarios for the analysed noise thresholds. For the 55 dB contour for RWY 12, its area was approximately 58.8% smaller than that of the conventional approach, while the CDO scenario resulted in a reduction of approximately 26.1%. The MAP scenario produced contour areas broadly comparable to those of the conventional approach. These findings demonstrate that changes in the approach profile can influence the spatial extent of aircraft noise contours and highlight the value of modelling alternative procedures to support airports, airlines, air navigation service providers, and relevant authorities in noise management and mitigation planning.

Key words: Aircraft noise, Airport, Noise indicators, Noise exposure, Approach procedures

1. INTRODUCTION

Aircraft noise is one of the main environmental impacts of airport operations, particularly in urban areas where residential areas are located close to airports and aircraft flight paths. During approach, aircraft fly at relatively low altitudes over the surrounding area, and the noise generated by these operations can affect nearby communities. Although aircraft characteristics and the number of operations are important factors, the flight path and the way an approach is performed can also influence the spatial distribution of aircraft noise.

Several approach procedures have been considered as possible means of reducing aircraft noise. Conventional

approaches provide a reference for comparing alternative procedures. Continuous Descent Operations (CDO) allow aircraft to descend with fewer level segments and reduced engine thrust, potentially reducing noise and fuel consumption [1, 2]. Another option is a steeper approach, which changes the aircraft's vertical flight path and may reduce noise levels in some areas beneath the approach path. Alternative aiming-point concepts can also modify the location of the final approach path and shift the resulting noise footprint. However, the effects of these procedures depend on the specific flight profile and operating conditions and therefore need to be assessed for each case [1].

Previous studies have examined the noise effects of alternative approach procedures at different airports. Serbezov et al. [2] evaluated the potential noise reduction associated with CDO implementation at Sofia Airport and found that the effects differed between runway directions. White et al. [3] compared the perceived annoyance caused by continuous descent and conventional approaches, showing that the effects also depend on the aircraft's flight profile and the location of the affected area. Options for modifying the final approach, including a steeper glide slope and displaced landing, were examined by the authors of [1]. In the context of Belgrade Airport, aircraft noise has also been investigated through measurements in nearby communities [4].

Aircraft noise is an important environmental concern around Belgrade Nikola Tesla Airport, particularly for residential communities located near the airport and beneath aircraft flight paths. To assess the extent of this problem, a Strategic Noise Map was prepared for the airport in 2024, providing a basis for the Environmental Noise Protection Action Plan for the period 2025–2030 [5]. The Action Plan identifies continuous descent operations (CDO) as one of the measures for aircraft noise management. According to EUROCONTROL's Aviation Intelligence Portal, 58.1% of arrivals at Belgrade Nikola Tesla Airport in 2025 were classified as CDO based on the portal's noise-related CDO indicator [6]. However, CDO has not yet been formally implemented at Belgrade Airport. This distinction highlights the importance of conducting simulations and assessing the potential noise

effects of different approach procedures. Such analyses can quantify the potential benefits of alternative procedures and provide technical evidence to support their future implementation as part of aircraft noise mitigation strategies.

The aim of this paper is to compare the noise contours obtained for different aircraft approach procedures at Belgrade Nikola Tesla Airport and to examine the differences in the areas covered by the resulting contours. The study provides a case-based comparison of the selected procedures and illustrates how changes in the approach profile can affect the spatial distribution of aircraft noise around the airport.

The remainder of the paper is organised as follows. Section 2 describes the methodology, including the modelled approach scenarios and the noise assessment procedure. Section 3 presents and discusses the results, while Section 4 summarises the main findings.

2. METHODOLOGY

2.1. Study Area and Aircraft Operation

The study was conducted for Belgrade Nikola Tesla Airport, Serbia. The Airbus A319 was selected as the representative aircraft type because it was the most frequently operated aircraft type at the airport. According to the 2023 aircraft movement data reported in the airport's strategic noise mapping documentation, the A319 accounted for 17,906 take-off and landing operations, representing 21% of all operations.

Landing operations were modelled for both runway directions, RWY 12 and RWY 30. The simulations were performed under the following atmospheric conditions: a temperature of 15 °C, atmospheric pressure of 1015.6 hPa, relative humidity of 76.5%, and a headwind of 8 kt.

Fig 1 illustrates the study area around Belgrade Nikola Tesla Airport, including the runway geometry and the straight-in approach paths considered for landing operations in both runway directions, RWY 12 and RWY 30. The same runway geometry and approach path alignment were used as the basis for all four approach scenarios.

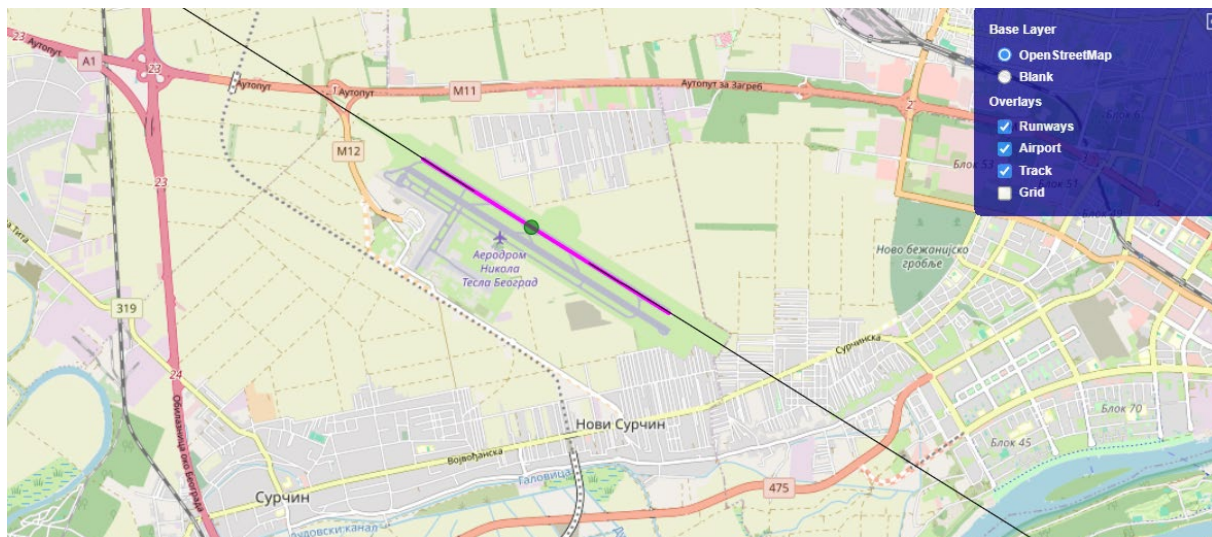


Fig. 1 Study area and modelled straight-in approach paths for landing operations at Belgrade Nikola Tesla Airport, for runway directions RWY 12 and RWY 30, as represented in EUROCONTROL IMPACT.

2.2. Approach and Landing Scenarios

Four approach scenarios were modelled: conventional approach, Continuous Descent Operations (CDO), steeper approach, and Multiple Aiming Points (MAP). The conventional approach profile was used as the reference scenario. Its initial descent segment was defined with an angle of 3.1°, while subsequent descent segments used an angle of 3.0°. The conventional profile also included intermediate level-flight segments at 3,000 ft.

The CDO profile consisted of successive descent segments with idle thrust and a descent angle of 3.0°, without intermediate level-flight segments in the modelled profile. The steeper approach scenario used a descent angle of 4.5° throughout the modelled descent segments. The MAP scenario was modelled by applying a fixed 1,500 m

displacement of the aiming point from its standard position.

Each scenario was simulated for both RWY 12 and RWY 30, resulting in eight individual landing simulations. The aircraft type and basic input parameters were kept consistent across the scenarios, while the approach profile or aiming-point position was modified according to the scenario.

2.3. Noise Modelling and Assessment Indicators

Noise calculations were performed using IMPACT version 3.42.A, applying the method described in ECAC Doc 29, 4th Edition. IMPACT stands for Integrated Aircraft Noise and Emissions Modelling Platform. Developed by EUROCONTROL, it is used to model the environmental impacts of aviation, including aircraft noise and emissions [7].

Terrain elevation data were obtained from NASA's Shuttle Radar Topography Mission (SRTM) Global 3 arc-second dataset and processed in ASCII grid (ASC) format. The terrain data were incorporated into the modelling workflow to represent the elevation of the area surrounding Belgrade Nikola Tesla Airport.

Two noise indicators were used: the maximum A-weighted sound level (L_{Amax}) and the single-event sound exposure level (SEL). L_{Amax} represents the highest A-weighted sound level reached during an individual aircraft operation, whereas SEL represents the sound exposure of the event normalised to a reference duration of one second.

Noise contours were generated at 5 dB intervals, from 40 to 90 dB, using a $100\text{ m} \times 100\text{ m}$ calculation grid. The areas enclosed by the contours were obtained from the IMPACT outputs and expressed in square kilometres. For each noise level, the area obtained for an alternative scenario was compared with the corresponding area for the conventional approach. The percentage change was calculated relative to the conventional scenario. Negative values indicate a smaller contour area than that of the conventional approach, whereas positive values indicate a larger contour area.

To ensure a consistent comparison, all four approach scenarios were evaluated using the same aircraft type, atmospheric conditions, wind conditions, noise modelling framework, and calculation grid. The scenarios differed only in the defined approach profile and, for the MAP scenario, the location of the aiming point. The resulting noise contours were evaluated using the same set of contour levels for each noise indicator and runway direction. This consistent modelling setup allows the differences in contour areas and spatial distribution to be examined in relation to the changes introduced in each approach scenario, while limiting the influence of other modelling parameters.

3. RESULTS AND DISCUSSION

The results are presented in terms of noise contour areas obtained for the four approach scenarios: conventional approach, continuous descent operations (CDO), steeper approach, and multiple aiming points (MAP) with a 1,500 m displacement of the aiming point. The analysis considers two noise indicators, L_{Amax} and SEL, and both runway directions, RWY 12 and RWY 30. For each indicator and runway direction, the areas enclosed by noise contours ranging from 40 to 90 dB, in 5 dB increments, are compared to assess the influence of the approach profile on the spatial distribution of predicted single-event aircraft noise.

3.1. L_{Amax} noise contour areas

The areas enclosed by L_{Amax} noise contours were calculated for each approach scenario and runway direction. The results for RWY 12 are presented first (Table 1), followed by those for RWY 30 (Table 2). Comparing the contour areas makes it possible to identify differences between the approach profiles at individual

noise levels and to determine whether these differences remain consistent across the two runway directions.

Table 1 Areas enclosed by L_{Amax} noise contours for the four approach scenarios on RWY 12 (km²)

L_{Amax} contour level (dB)	Conventional approach	CDO	Steeper approach (4.5°)	Multiple aiming points
40	261.25	215.39	81.78	261.24
45	187.06	152.55	58.00	187.04
50	123.96	98.37	40.29	123.87
55	64.63	47.78	26.60	64.63
60	24.59	22.37	15.09	24.57
65	12.66	10.33	7.00	12.66
70	5.77	4.42	3.01	5.76
75	2.47	1.85	1.26	2.46
80	1.00	0.71	0.49	1.00
85	0.38	0.23	0.16	0.38
90	0.12	0.06	0.04	0.12

Table 1 presents the L_{Amax} contour areas for RWY 12. The results indicate clear differences between the four approach scenarios, with the magnitude of these differences depending on the contour level. The conventional approach and the MAP scenario produce very similar contour areas across the examined noise levels, with differences generally negligible in relative terms. The primary objective of the MAP procedure, however, is to shift the noise footprint closer to the runway, towards an area with no residential population, rather than necessarily reducing the total area enclosed by the noise contours.

The CDO scenario results in smaller contour areas than the conventional approach. For the 55 dB contour, the area decreases from 64.63 km² for the conventional approach to 47.78 km² for CDO, representing a reduction of approximately 26.1%. At the 40 dB contour level, the reduction is approximately 17.6%, while at 70 dB it is approximately 23.3%. The steeper approach produces the smallest contour areas among the four scenarios. Compared with the conventional approach, the area enclosed by the 55 dB contour decreases to 26.60 km², a reduction of approximately 58.8%. The reductions are even more pronounced at the 40 dB contour level, where the area decreases by approximately 68.7%. These results indicate that the steeper approach has the strongest effect on reducing the spatial extent of the modelled L_{Amax} contours, while CDO also provides a considerable reduction relative to the conventional approach.

The spatial distribution of L_{Amax} noise contours for the four approach scenarios on RWY 12 is illustrated in Fig 2. The conventional approach and CDO produce similarly oriented noise footprints, although the contours for CDO cover a smaller area. The steeper approach results in a substantially more compact noise footprint, consistent with the reductions in contour areas reported in Table 1. In contrast, the MAP scenario retains an elongated footprint similar to that of the conventional approach, but shifts its spatial distribution in accordance with the displaced aiming point. This comparison illustrates the distinction between reducing the overall contour area and relocating the noise footprint, which may have different implications for noise exposure in surrounding residential areas.

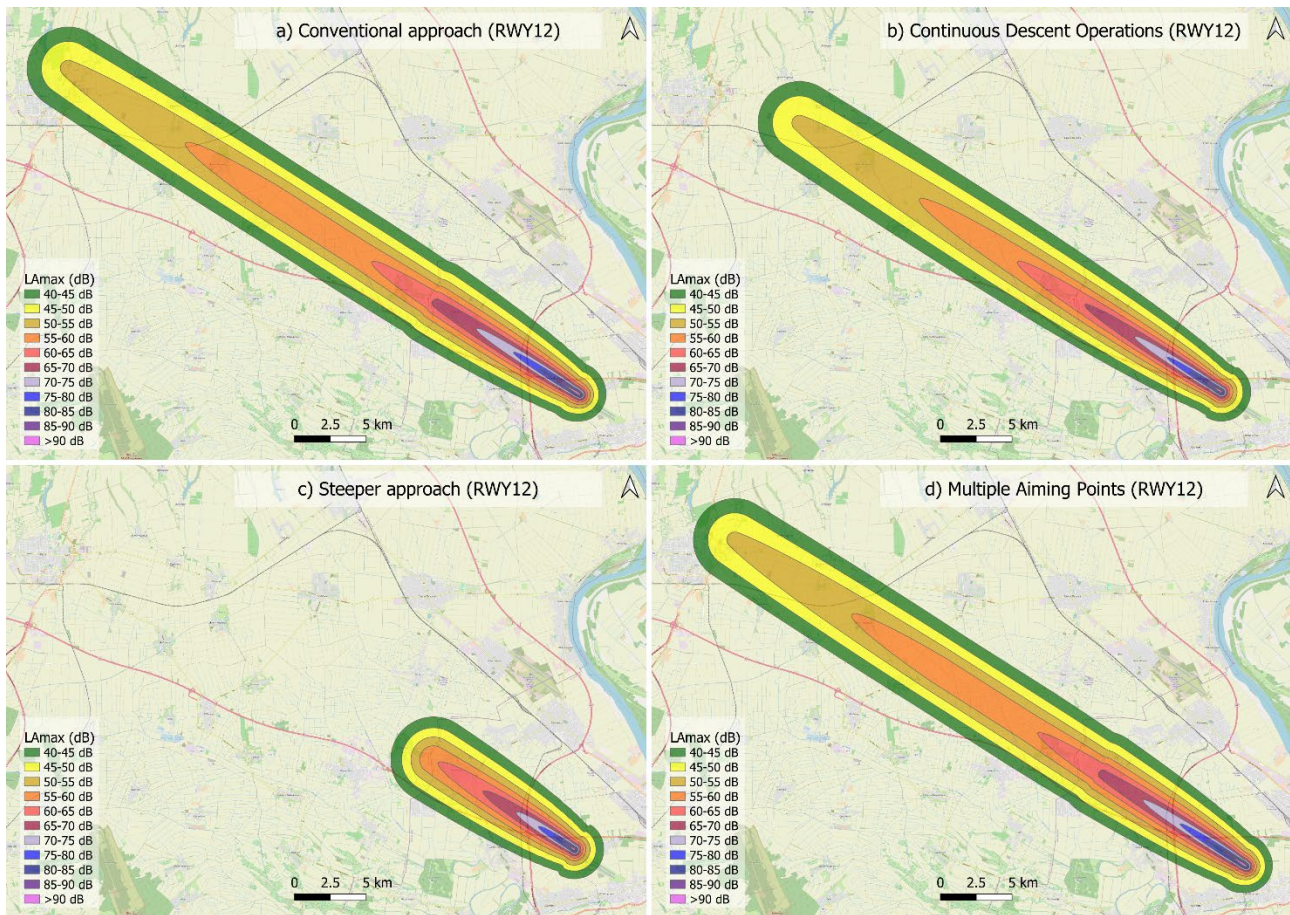


Fig. 2 Comparison of L_{Amax} noise contours for four approach scenarios to RWY 12 at Belgrade Nikola Tesla Airport: (a) conventional approach, (b) continuous descent operations (CDO), (c) steeper approach (4.5°), and (d) multiple aiming points (MAP) with a 1,500 m displacement of the aiming point.

The following analysis examines whether the effects of the different approach scenarios on L_{Amax} contour areas observed for RWY 12 are also reflected in the results for RWY 30 (Table 2).

Table 2 Areas enclosed by L_{Amax} noise contours for the four approach scenarios on RWY 30 (km²)

L_{Amax} contour level (dB)	Conventional approach	CDO	Steeper approach (4.5°)	Multiple aiming points
40	261.73	215.56	81.80	261.67
45	187.70	152.58	58.01	187.66
50	125.61	97.79	40.29	125.31
55	64.05	47.24	26.60	63.97
60	24.47	22.25	15.07	24.48
65	12.64	10.30	6.97	12.65
70	5.74	4.40	3.00	5.74
75	2.46	1.84	1.26	2.46
80	1.00	0.71	0.49	1.00
85	0.38	0.23	0.16	0.38
90	0.13	0.07	0.04	0.12

The results for RWY 30, presented in Table 2, show clear differences between the four approach scenarios. The conventional approach and the MAP scenario produce very similar contour areas across the examined noise levels. For the 55 dB contour, the area decreases slightly from 64.05

km² for the conventional approach to 63.97 km² for MAP, a reduction of only approximately 0.1%.

The CDO scenario produces smaller contour areas than the conventional approach. At the 55 dB contour level, the area decreases from 64.05 km² to 47.24 km², corresponding to a reduction of approximately 26.2%. At 40 dB, the reduction is approximately 17.6%, while at 70 dB it is approximately 23.3%. The steeper approach produces the smallest contour areas among all four scenarios. At the 55 dB contour level, the area decreases to 26.60 km², representing a reduction of approximately 58.5% compared with the conventional approach. At 40 dB, the reduction reaches approximately 68.8%. These results indicate that the steeper approach has the strongest effect on reducing the spatial extent of the modelled L_{Amax} contours, while CDO also provides a considerable reduction.

The overall ordering of the scenarios is consistent with the results obtained for RWY 12: the steeper approach produces the smallest contour areas, followed by CDO, whereas the conventional approach and MAP yield very similar results. Although the absolute contour areas differ slightly between the two runway directions, the relative differences between the approach scenarios remain broadly comparable. These findings suggest that the influence of the modelled approach profile on L_{Amax} contour areas is evident for both runway directions. However, the results

represent individual simulated landing events and should not be interpreted directly as reductions in population exposure or long-term community noise impact.

Given the similar overall patterns observed for the two runway directions, the graphical comparison of noise contour distributions is limited to RWY 12 for L_{Amax} , while the results for both runway directions are retained in the tables.

3.2. SEL noise contour areas

In addition to L_{Amax} , the analysis considered the single-event sound exposure level (SEL), which accounts for the sound energy accumulated over the aircraft noise event and normalizes it to a reference duration of one second. The SEL contours complement the L_{Amax} results by providing a different characterization of the noise event. As in the previous subsection, contour areas were calculated for levels from 40 to 90 dB in 5 dB increments for both runway directions.

Table 3 Areas enclosed by SEL noise contours for the four approach scenarios on RWY 12 (km²)

SEL contour level (dB)	Conventional approach	CDO	Steeper approach (4.5°)	Multiple aiming points
40	744.94	621.97	262.92	745.28
45	542.25	448.72	176.79	542.40
50	393.36	322.52	118.97	393.45
55	276.01	224.07	80.54	276.05
60	184.37	148.30	54.10	184.36
65	106.24	83.66	35.57	106.21
70	50.28	38.70	21.82	50.21
75	19.18	14.72	9.81	19.18
80	8.11	5.06	3.37	8.11
85	2.55	1.57	1.04	2.53
90	0.72	0.36	0.24	0.71

Table 3 presents the SEL contour areas for RWY 12. The results show that both CDO and the steeper approach produce smaller contour areas than the conventional approach, although the magnitude of the reduction varies with the contour level. Since the MAP scenario differs from the conventional approach only in the 1,500 m displacement of the aiming point, substantial differences in the total contour areas are not expected. Assessing the benefit of this procedure would require a spatial analysis of the noise contours in relation to the distribution of the population.

For the 55 dB SEL contour, the area decreases from 276.01 km² for the conventional approach to 224.07 km² for CDO, corresponding to a reduction of approximately 18.8%. The steeper approach produces a substantially smaller area of 80.54 km², representing a reduction of approximately 70.8% compared with the conventional approach. At the 40 dB contour level, the reductions are approximately 16.5% for CDO and 64.7% for the steeper approach, while at 70 dB they are approximately 23.0% and 56.6%, respectively. These results indicate that the relative effect of the approach profile varies across the SEL contour levels, with the steeper approach consistently producing the smallest contour areas.

The differences between scenarios are also evident in the SEL results, although their magnitude does not

necessarily match the differences observed for L_{Amax} . This is expected because the two indicators describe different characteristics of the noise event: L_{Amax} represents the maximum A-weighted sound level, whereas SEL represents the sound exposure associated with the event. Consequently, the relative effect of changing the approach profile depends on the indicator used to characterize the noise contours.

Table 4 Areas enclosed by SEL noise contours for the four approach scenarios on RWY 30 (km²)

SEL contour level (dB)	Conventional approach	CDO	Steeper approach (4.5°)	Multiple aiming points
40	745.97	622.95	263.12	746.23
45	542.67	449.16	176.88	542.77
50	393.89	322.93	119.03	393.91
55	276.51	224.34	80.56	276.56
60	185.19	148.23	54.11	185.03
65	107.05	83.08	35.57	107.04
70	49.76	38.43	21.81	49.66
75	19.13	14.67	9.77	19.15
80	8.11	5.03	3.36	8.07
85	2.53	1.57	1.04	2.53
90	0.71	0.36	0.24	0.72

Table 4 presents the SEL contour areas for RWY 30. The results show that the reductions in contour area achieved by CDO and the steeper approach are consistent with those observed for RWY 12. The CDO scenario reduces the area enclosed by the 55 dB contour from 276.51 km² for the conventional approach to 224.34 km², corresponding to a reduction of approximately 18.9%. The reduction is more pronounced for the steeper approach, for which the area decreases to 80.56 km², representing a reduction of approximately 70.9%. At the 40 dB contour level, the corresponding reductions are approximately 16.5% for CDO and 64.7% for the steeper approach, while at 70 dB they are approximately 22.8% and 56.2%, respectively.

As in the other scenarios, the MAP contour areas remain very similar to those of the conventional approach. At the 55 dB level, the difference between the two scenarios is negligible, with areas of 276.51 km² and 276.56 km², respectively.

Overall, the SEL results for RWY 30 confirm the pattern observed for RWY 12: the steeper approach produces the smallest contour areas, followed by CDO, while the conventional approach and MAP yield almost identical areas. The consistency of these results across both runway directions indicates that the relative effects of the modelled approach profiles are similar for the two runway directions. Nevertheless, these area-based comparisons alone do not establish the extent to which the scenarios would reduce the number of people exposed to aircraft noise; this would require a spatial assessment incorporating population distribution.

As the SEL results also show similar overall patterns for both runway directions, only the noise contours for RWY 30 are presented graphically. This complements the L_{Amax} contour maps for RWY 12 presented in Figure 2 and avoids redundant graphical representations while retaining the quantitative results for both runway directions in the tables.

Figure 3 illustrates the spatial distribution of SEL noise contours for the four approach scenarios on RWY 30. The conventional approach and MAP scenario produce similarly elongated noise footprints, whereas the CDO scenario results in a smaller spatial extent. The steeper approach produces the most compact footprint, in agreement with the contour areas reported in Table 4. The

maps also show that changes in the approach profile affect not only the total area enclosed by the contours but also their spatial distribution. In particular, the MAP scenario should be evaluated in terms of the location of its noise footprint relative to residential areas, rather than solely by comparing total contour areas.

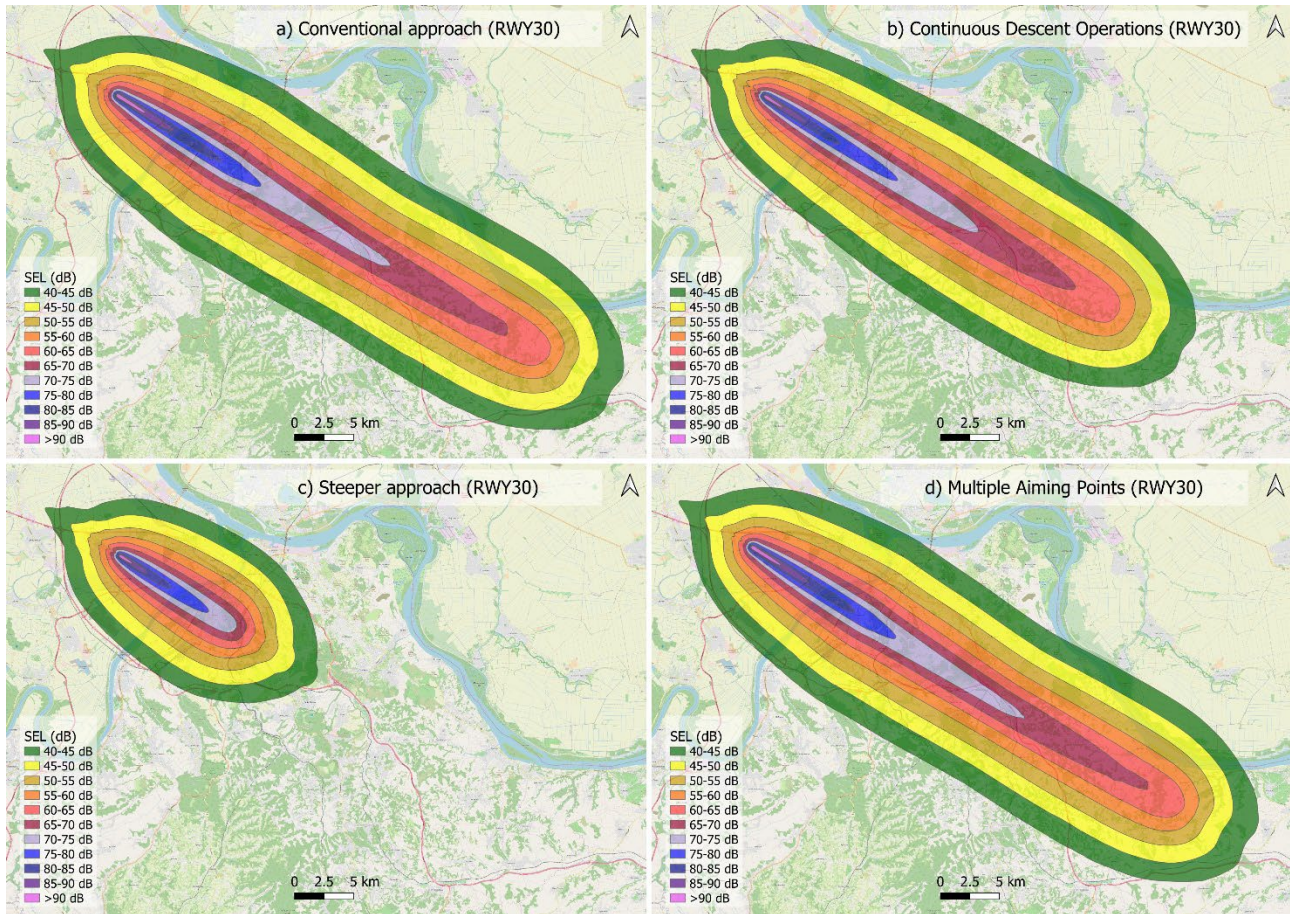


Fig. 3 Comparison of SEL noise contours for four approach scenarios to RWY 30 at Belgrade Nikola Tesla Airport: (a) conventional approach, (b) continuous descent operations (CDO), (c) steeper approach (4.5°), and (d) multiple aiming points (MAP) with a 1,500 m displacement of the aiming point.

3.3. Comparative discussion

Taken together, the results for L_{Amax} and SEL indicate that the steeper approach scenario produces the smallest noise contour areas among the four modelled scenarios. CDO also reduces the contour areas relative to the conventional approach, although the magnitude of the difference varies with the noise indicator and contour level. In contrast, the MAP scenario, which shifts the aiming point by 1,500 m, produces areas that are broadly similar to those obtained for the conventional approach.

These findings highlight the importance of the vertical approach profile when assessing the spatial distribution of aircraft noise during landing. However, the results represent modelled single-event contours for an Airbus A319 under the specified atmospheric and wind conditions. They do not quantify the number of people exposed to aircraft noise, cumulative exposure from multiple operations, or the overall environmental benefit of implementing a particular procedure. Further assessment

using operational traffic data, representative distributions of aircraft types and procedures, and population data would be required to evaluate the implications for long-term noise exposure around Belgrade Airport.

A comparison of the two noise indicators reveals that the relative effect of the approach scenarios depends on the metric used to describe the noise event. For the 55 dB contour, the CDO scenario reduces the L_{Amax} contour area by approximately 26% for both runway directions, whereas the reduction in SEL contour area is approximately 19%. The steeper approach produces a more pronounced reduction for both indicators, although the magnitude differs: the reduction in L_{Amax} contour area is approximately 59%, compared with approximately 71% for SEL. These comparisons demonstrate that the estimated effect of an approach procedure depends not only on the flight profile but also on the noise indicator used in the assessment.

The results also highlight the distinction between reducing the area enclosed by a noise contour and changing

its geographical location. While CDO and the steeper approach reduce the contour areas in the modelled scenarios, the MAP procedure primarily changes the location of the noise footprint by displacing the aiming point. Consequently, contour area alone is insufficient to assess the potential benefit of MAP for nearby communities. A spatial overlay of noise contours and population distribution would be needed to determine whether the relocation results in fewer residents exposed to relevant noise levels. This distinction is important when considering the potential application of alternative approach procedures as aircraft noise mitigation measures at Belgrade Airport.

3.4. Implications for aircraft noise management

The comparison of alternative approach scenarios provides useful information for the assessment of potential aircraft noise mitigation measures. However, the interpretation of noise contour areas requires consideration of both the selected noise indicator and the geographical distribution of the resulting noise footprint. A reduction in the area enclosed by a particular contour indicates a smaller spatial extent of the modelled noise level, but it does not necessarily imply a proportional reduction in the number of people exposed to that level. The relationship between contour area and population exposure depends on the location of the contours in relation to residential areas and the distribution of the population within the study area.

This distinction is particularly relevant when comparing the CDO, steeper approach, and MAP scenarios. The smaller contour areas obtained for CDO and the steeper approach indicate the potential of these approach profiles to reduce the spatial extent of single-event noise contours under the simulated conditions. Nevertheless, the practical significance of these reductions depends on where the changes occur. A relatively small reduction in contour area could be important if it affects a densely populated area, whereas a larger reduction in a sparsely populated area might have a more limited effect on the number of residents exposed. Similarly, the MAP procedure may offer a potential benefit by relocating the noise footprint, even when the total area enclosed by the contours remains almost unchanged.

For the purposes of aircraft noise action planning, these findings support a multi-criteria assessment of alternative mitigation measures. In addition to comparing contour areas, further evaluation should consider population exposure, the location of sensitive receptors, the frequency of aircraft operations, and the operational feasibility of the proposed procedures. The results of single-event simulations can serve as an initial screening tool to identify scenarios that warrant more detailed investigation. Subsequent analyses incorporating representative traffic distributions and population data could then be used to estimate the potential effects of these scenarios on community noise exposure. This staged approach would provide decision-makers with a more comprehensive basis for comparing mitigation options and prioritising measures for further assessment at Belgrade Airport.

4. CONCLUSIONS

This study compared four approach scenarios for an Airbus A319 at Belgrade Nikola Tesla Airport: a conventional approach, continuous descent operations (CDO), a steeper approach with a 4.5° descent angle, and a multiple aiming points (MAP) procedure with a 1,500 m displacement of the aiming point. The results showed that the steeper approach produced the smallest noise contour areas for both L_{Amax} and SEL, while CDO also reduced the contour areas compared with the conventional approach. In contrast, the MAP scenario produced contour areas similar to those of the conventional approach, as the approach profile remained unchanged and only the aiming point was displaced. These findings demonstrate that different approach modifications can affect both the extent and the spatial distribution of single-event aircraft noise.

The results may support airport operators, air navigation service providers, aviation authorities, and other decision-makers involved in aircraft noise management. In particular, the modelling approach presented in this study can contribute to the preparation and evaluation of aircraft noise action plans by enabling alternative approach procedures to be compared under consistent conditions. Such comparisons can help identify measures with the greatest potential to reduce noise contour areas and determine which options warrant further operational and environmental assessment. However, the selection of mitigation measures should not be based on contour area alone. For example, the potential benefit of the MAP procedure depends primarily on whether relocating the noise footprint reduces noise exposure in residential areas. The results of this study should therefore be considered an initial basis for decision-making rather than a direct assessment of the reduction in population exposure.

Several directions for future research can extend the present analysis. First, the noise contours should be combined with population distribution data to estimate the number of residents exposed at different noise levels and to assess the effects of each approach scenario on population exposure. Second, the analysis could be expanded to include additional aircraft types, different approach weights and configurations, a wider range of meteorological conditions, and representative operational traffic data. This would allow the assessment to better reflect actual airport operations and support the estimation of cumulative noise exposure. Further research could also investigate the sensitivity of the results to changes in descent angle, aiming-point displacement, and other approach parameters, as well as examine the implications of alternative procedures for both runway directions. Finally, the model predictions could be compared with measured aircraft noise data to evaluate their agreement with observed conditions. Together, these extensions would provide a more comprehensive evidence base for assessing the effectiveness and practical feasibility of aircraft noise mitigation measures and for supporting the development of future noise action plans at Belgrade Airport.

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NOISE IN THE ZONE OF INFLUENCE OF HVAC SYSTEMS OUTPUT UNITS – METHOD AND PLACE OF INSTALLATION

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Abstract. *When installing the output units of HVAC systems in commercial facilities, it is necessary to pay particular attention to the installation position and conditions to avoid noise disturbance in the surrounding environment, both outdoors and indoors, within the zone of influence. For the system to function properly, the output units should be installed where the flow of fresh air is as good as possible, usually outdoors and most often on the building facade. However, the noise they generate must not disturb people in the surrounding area. The acoustic zone to which the outdoor location belongs should also be taken into account. This paper examines the topic through examples of HVAC system noise measurements at retail outlets selling mass-market goods in a chain of stores belonging to the same owner.*

Key words: *Noise, HVAC system, Reference measuring point, Installation*

1. INTRODUCTION

During the noise measurement of the HVAC systems output units of retail outlets in the chain of stores of the same legal owner, a question appeared regarding the position of their installation. In the most common case, such stores are located in residential and commercial units, so it is very important to carefully choose the place and conditions for placing the mentioned output units, so as not to exceed the noise limit values during their operation. In most cases, the output units are installed on the facade of the building, but also on the ground if they are larger. Example include the output units that are used for cooling the air conditioning chambers for storing fresh and frozen food, which means that they work continuously 24 hours a day, but also for the air conditioning of business and sales spaces according to needs.

The Laboratory for Acoustics and Vibrations of the Institute IMS ad Belgrade has performed a large number of noise measurements on this topic in a period of one year in accordance with standards and legal regulations [1-5] from which certain conclusions can be drawn that can help with basic problem solving, even before the actual installation. In solving the problem, a designer must be involved who would predict the position of the noise source in relation to residential or business units that may be potentially endangered, including appropriate calculations and rules [12,13,14].

In some cases, measurements were carried out at new, sometimes unfinished residential and commercial buildings, where it is easier to solve a potential problem before residents or users move in. Resolving problems is more difficult in already occupied buildings when noise disturbs the surrounding area and residents or users have already made complaints. Such noise disturbance can create stressful situations for both the owner of the noise source and the affected residents, often involving the competent inspection authority.

Table 1 Limit values of noise indicators outdoors

Zone	Purpose of space	Noise level dB(A)	
		day and evening	night
1	Rest and recreation areas, hospital zones and convalescent centers, cultural and historical sites, large parks	50	40
2	Tourist areas, camps and school zones	50	45
3	Purely residential areas	55	45
4	Business-residential areas, commercial-residential areas and children's playgrounds	60	50
5	City center, craft, trade, administrative zone with apartments, zone along highways, highways and city roads	65	55
6	Industrial, storage and service areas and transport terminals without residential buildings	At the border of this zone, the noise must not exceed the limit value in the bordering zone	

Measurements are performed indoors and outdoors at the reference measurement points (closest to the source). During these measurements, the noise of a specific source is evaluated according to legally set limit values. In the environment the indoor limit values in apartments (bedroom and living room) with closed windows are 35 dB(A) for day and evening and 30 dB(A) for night, while outdoors the limit values in the cities of Serbia that

are acoustically zoned are presented in Table 1 [4], and otherwise they are determined according to Article 17 of the Law [5], which are the values corresponding to zone 5 from Table 1. It should be taken into account that only zones 3, 4 and 5 are important for the noise of the output units.

2. SELECTION OF THE MEASUREMENT POINTS

In all cases involving the chain of stores examined in this study, priority was given to outdoor measurements at the reference measurement points, in accordance with the client's request. However, depending on site conditions (whether the building was in use, where and how the noise sources were installed, etc.), indoor measurements were also taken, where possible, if the installation method was considered to pose a risk of indoor noise disturbance [6,7].

The client generally required measurements before citizens would potentially report to the competent inspection service. With this, he wanted to ensure that there is no noise pollution in order to protect the environment.

In the case of choosing measurement points outdoors, one should take a good look at the layout of potentially endangered residential or commercial units – both windows and facades of apartments, as well as their terraces, and in some cases also courtyards.

Through the examples given in the paper, it will be shown how important it is to choose adequate measuring points for measuring the noise of sources such as the output units of the HVAC systems.

2.1. Example 1 - Measuring point between two potentially endangered objects

This example [8] presents a situation where the noise sources are located directly under an apartment terrace, but their installation on the facade or on the ground means that they are completely shielded from the terrace. On the other hand, they are directed towards a nearby residential house (Fig. 1). The building is new and unoccupied, so it was not possible to take measurements in the apartment above. Since, the apartment is shielded from the sources by the terrace, the choice of an outdoor measurement point was logical. Measurements were required in the direction of sound propagation from the sources, at the property boundary towards the potentially affected house (Fig. 2).



Fig. 1 Noise sources on the facade



Fig. 2 Position of the noise sources on the map

2.2. Example 2 - Noise sources next to the facade of the apartment

In this example [9], the HVAC system output units are installed on the ground, slightly below ground-floor level, next to the facade of the building's ground-floor apartment (Fig. 3).

Given that the output units are directly under the window and the terrace of the apartment, it could be concluded that the environment in the outdoors area is quite endangered and there is no need to measure indoors, so the selection of the measurement place was clear, and the situation is shown in the sketch (Fig. 4).



Fig. 3 Noise sources below the ground floor level

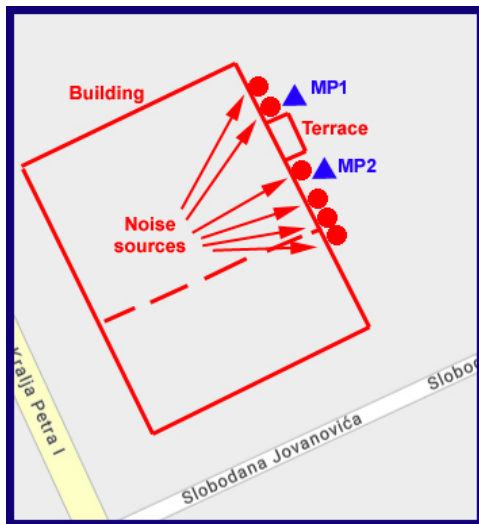


Fig. 4 The sketch of the noise sources position

2.3. Example 3 - Noise sources under the ceiling towards the apartment

In this example [10], the output units of the air conditioning chambers located in the warehouse area are installed on the chambers themselves (Fig. 5), while the ventilation grids of the output channels of this system are located on the glass facade under the window of the nearest apartment (Fig. 6) through which fans for removing the warm air created by the operation of the output units can be heard.

Measurements outdoors on the reference point, and according to the order of the client, included the measurement point in the courtyard part of the building, in the parking lot next to the building's facade, where it was concluded that the measured level exceeded the limit value defined in accordance with the acoustic zone to which the reference point belongs. In this case, the question can be raised as to who should be protected from noise next to the facade of the building from the inside, where there are no passers-by or people staying there, even though this area is part of the environment.

However, as the entire described system is under the ceiling towards the apartment, there is a possibility of noise pollution indoors, i.e. in the room of the apartment. For this reason, new reference measurement points in the apartment were selected, and thus, in addition to the measurements outdoors through the window of the apartment, the additional task of measuring indoors was also fulfilled.



Fig. 5 Noise sources on the chambers themselves



Fig. 6 Exhaust bars below the apartment

2.4. Example 4 - Noise sources near the courtyard part of the apartment

This example [11] shows a specific case of the architectural solution of a residential-business building where there is an exit (balcony door) from the apartment to the open courtyard area of the building on the ground floor (Figs. 7 and 8). Assuming that this space will be used as a living space, that is, as a terrace of the mentioned apartment, then it should be protected from noise, where the output units of HVAC system are already installed.



Fig. 7 Noise sources in courtyard area

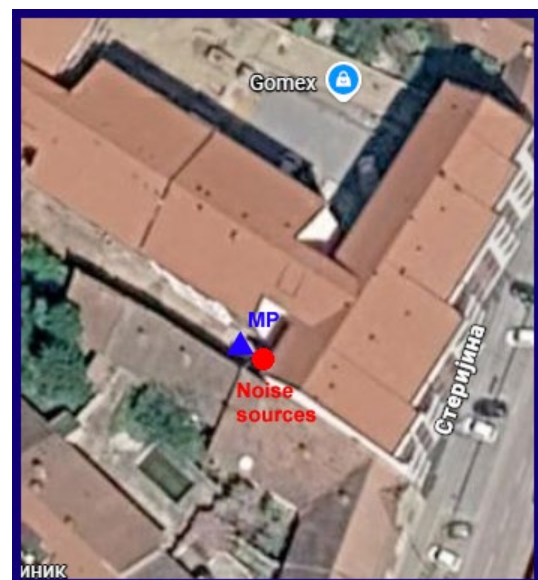


Fig. 8 Position of the noise sources on the map

3. ANALYSIS OF THE MEASUREMENT RESULTS

Through the mentioned examples of the selection of measuring points in this chapter the measurement results and their analysis are presented for the previously mentioned characteristic cases. The results of measurements at selected reference measurement points are shown with ratings of the limit level outdoors and/or indoors in the environment.

At the end of the chapter, a table with frequency-measured noise levels (Table 6) for each of the four examples is presented and a comparative diagram for measurements outdoors is drawn (Fig. 9).

3.1. Example 1 – Measuring point between two potentially endangered objects

Although the results of measurements at two different distances from the noise sources are presented, for Table 6 and the comparative diagram in Fig. 9, the measurement closer to the source of noise was chosen as a more critical case (at approximately 4 m distance from the sources) and not the measurement at the boundary of the property which is further away from the source as already described in chapter 2.

Table 2 Example 1 - Measurement results [8]

Measuring point	Border (MP1)	At $\approx$ 4 m (MP2)
Residual sound:		
Rating level:	$L_{AeqT0} = 41.3$ dB	$L_{AeqT0} = 39.8$ dB
Total sound:		
Initial sound:	$L_{AeqT1} = 51.9$ dB	$L_{AeqT1} = 54.9$ dB
Rating level:	$L_{RAeqT1} = 51.9$ dB	$L_{RAeqT1} = 54.9$ dB
Specific sound:		
Correction:	-0.4 dB	-0.1 dB
Rating level:	$L_{RAeqT1} = 51.5$ dB	$L_{RAeqT1} = 54.8$ dB
Uncertainties:	$U = 1.16$ dB	$U = 1.04$ dB

The evaluation of the relevant noise level was carried out according to the Regulation [4] for limit values outdoors which are 65 dB(A) for day-evening and 55 dB(A) for night, taking into account Article 17 of the Law [5], based on which the location in question belongs to the presumed acoustic zone 5 (the city is not zoned).

Therefore, the rating levels of total sound and of specific sound outdoors, on the boundary of the property towards the nearest house (MP1) and at a distance of about 4 m from the noise sources (MP2) **do not exceed** the limit value for the day-evening and night reference time interval, from the aspect of the mentioned Regulation [4].

3.2. Example 2 – Source of noise next to the facade of the apartment

Although the results of measurements at two different positions for the reference measuring points outdoors (left and right of the terrace of the apartment) are presented here, for Table 6 and the comparative diagram in Fig. 9, the measurement is selected for the sources on the right, and according to the more critical (higher) total level during the measurement.

The evaluation of the relevant noise level was carried out according to the Regulation [4] for limit values outdoors which are 65 dB(A) for day-evening and 55 dB(A) for night, taking into account Article 17 of the

Law [5], based on which the location in question belongs to the presumed acoustic zone 5 (the city is not zoned).

Table 3 Example 2 - Measurement results [9]

Measuring point	Right (MP1)	Left (MP2)
Residual sound:		
Rating level:	$L_{AeqT0} = 41.7$ dB	$L_{AeqT0} = 41.7$ dB
Total sound:		
Initial sound:	$L_{AeqT1} = 64.0$ dB	$L_{AeqT1} = 56.0$ dB
Tone corr. (200 Hz):	+5 dB	+5 dB
Rating level:	$L_{RAeqT1} = 69.0$ dB	$L_{RAeqT1} = 61.0$ dB
Specific sound:		
Correction:	–	-0.2 dB
Rating level:	$L_{RAeqT1} = 69.0$ dB	$L_{RAeqT1} = 60.8$ dB
Uncertainties:	$U = 1.01$ dB	$U = 1.05$ dB

Therefore, the rating levels of total sound and of specific sound outdoors, to the right of the terrace of the nearest residential unit above the noise source (MP1) **EXCEED** the limit value for both the day-evening and the night reference time interval, while to the left of the terrace of the nearest residential unit above the noise source (MP2) **do not exceed** the value for day-evening, and **EXCEED** the limit value for the night reference time interval, from the aspect of the mentioned Regulation [4].

3.3. Example 3 – Noise source under the ceiling towards the apartment

Measurements at the newly selected measurement points showed that the limit values were not exceeded either outdoors or indoors. Consequently, only these measurements were used in the subsequent assessment so that the client would not be burdened with additional investments in noise protection projects. The difference between the noise level measured through the apartment window and that measured on the sidewalk (both outdoors) can be explained by the direction of sound propagation. Sound propagated directly through the grilles towards the measurement point on the sidewalk, whereas the window was above the main direction of sound propagation and was not directly exposed to the sound waves. The sound intensity was therefore lower at the window, even though measurement point MP2 is closer to the noise source.

Table 4 Example 3 - Measurement results [10]

Measuring point	Room (MP1)	Window (MP2)
Residual sound:		
Rating level:	–	–
Total sound:		
Initial sound:	$L_{AeqT1} = 22.9$ dB	$L_{AeqT1} = 44.7$ dB
Rating level:	$L_{RAeqT1} = 22.9$ dB	$L_{RAeqT1} = 44.7$ dB
Specific sound:		
Correction:	–	–
Rating level:	–	–
Uncertainties:	–	–

The evaluation of the relevant noise level was carried out according to the Regulation [4] for the limit values indoors which are 35 dB(A) for day-evening and 30 dB(A) for night and outdoors which are 55 dB(A) for day-evening and 45 dB(A) for night, taking into account the Law [5], based on which the location in question belongs to acoustic zone 3.

Therefore, the rating levels of total sound and of specific sound in the bedroom (indoor, MP1) and through the window of the bedroom (outdoors, MP2) **do not exceed** the limit value for the day-evening and for the night reference time interval, from the aspect of the mentioned Regulation [4].

It should be noted that in this case the mentioned sources were not turned off during the measurement in order to measure the level of residual sound because the measurement results are sufficiently below the limit values at the reference measurement points, and it was safely concluded on the spot that the residual sound has no effect on the total sound, both outdoors and indoors of the reference measurement point.

3.4. Example 4 - Noise sources near the courtyard part of the apartment

Only one measurement was presented and that was outdoors.

In this case, the selection of the measurement point in an unoccupied building was also only outdoors under the assumption that it will exceed the limit value and that the remediation and/or relocation of the noise sources must be carried out immediately.

Table 5 Example 4 - Measurement results [11]

Measuring point	Courtyard (MP)
Residual sound:	
Rating level:	$L_{AeqT0} = 38.5$ dB
Total sound:	
Initial sound:	$L_{AeqT1} = 61.3$ dB
Tone corr. (200 Hz):	+5 dB
Rating level:	$L_{RAeqT1} = 66.3$ dB
Specific sound:	
Correction:	–
Rating level:	$L_{RAeqT1} = 66.3$ dB
Uncertainties:	$U = 1.00$ dB

The evaluation of the relevant noise level was carried out according to the Regulation [4] for limit values outdoors which are 55 dB(A) for day-evening and 45 dB(A) for night, taking into account the Law [5], based on which the location in question belongs to acoustic zone 3.

Therefore, the rating levels of total sound and specific sound outdoors, in the courtyard adjoining the apartment (MP), **EXCEED** the limit value for both day-evening and night reference time intervals under the Regulation [4].

3.5. Comparative presentation of the outdoor measurement results for four examples

Frequency analysis of measured values for all four examples is presented in Table 6, in the frequency spectrum of importance for noise measurement (50 Hz to 10 kHz), in accordance with the appropriate standards [1,2]. In the same table, in the last row, the total level (AP-All Pass) is given for the corresponding measurement, evaluated with corrections relevant to the residual sound level in two cases (Examples 1 and 2 for left sources) and to the highlighted tone (Examples 2 and 4), in accordance with the same standards [1,2]. Measured values that are below the audibility threshold of 20 dB(A) in the table are specially marked with an asterisk, and were included in the

calculation of the total sound level. All measurement values outdoors from the above table are shown in the diagram Fig. 9 in order to obtain a visualization of the presented values.

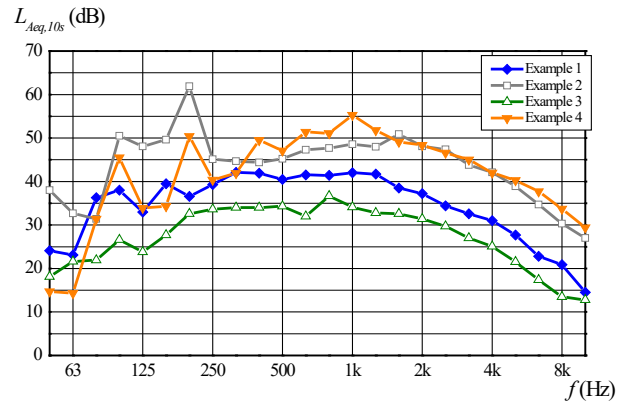


Fig. 9 Comparative diagram of 1/3 oct frequency analysis of all four examples for measurements outdoors

The limit values according to the Rulebook and Regulation [3,4] outdoors of the environment were not exceeded in Examples 1 and 3, while they were exceeded in Examples 2 and 4, where the characteristic highlighted tones were based on which a correction of +5 dB was added to the measured total value in the frequency range of importance for measurement in accordance with Annex K of the relevant standard [2].

When measuring indoors (Example 3), there was no exceeding of the noise level.

Table 6 One-third-octave frequency analysis (all four examples)

f (Hz)	$L_{Aeq,T}$ (dB)				
	Example				
	1	2	3	4	
1/3 oct	Outdoors	Outdoors	Outdoors	Indoors	Outdoors
50	24.1	38.0	18.1*	0.4*	14.7*
63	23.1	32.7	21.6	0.7*	14.3*
80	36.3	31.4	21.9	0.9*	31.4
100	38.0	50.5	26.6	5.8*	45.5
125	33.0	48.1	23.8	3.5*	33.9
160	39.5	49.6	27.7	8.5*	34.3
200	36.6	61.9	32.6	9.4*	50.4
250	39.3	45.1	33.6	10.0*	40.4
315	42.1	44.7	34.0	10.0*	41.9
400	41.9	44.4	34.0	9.1*	49.5
500	40.5	45.2	34.3	12.5*	47.1
630	41.5	47.3	32.0	11.7*	51.4
800	41.4	47.7	36.7	10.0*	51.1
1 k	42.0	48.6	34.1	12.0*	55.3
1.25 k	41.7	48.0	32.8	10.1*	51.8
1.6 k	38.5	50.9	32.6	8.7*	49.1
2 k	37.2	48.1	31.4	8.2*	48.4
2.5 k	34.4	47.4	29.7	9.4*	46.6
3.15 k	32.6	43.8	27.0	8.8*	45.0
4 k	31.0	42.1	25.1	9.9*	42.0
5 k	27.7	38.9	21.5	10.7*	40.3
6.3 k	22.8	34.7	17.4*	9.6*	37.7
8 k	20.9	30.3	13.5*	9.1*	33.7
10 k	14.5*	27.0	12.8*	7.3*	29.4
AP	51.5	69.0	44.7	22.9	66.3

* level values below 20 dB

On the diagram shown at Fig. 9, the characteristic frequency curves of the HVAC systems can be observed for all four examples, even the expected elevated levels at low frequencies [12], especially the highlighted tone at 200 Hz (tonality) in Examples 2 and 4, which was the reason for the correction of the total level. At high frequencies, there were no examples of elevated levels that could affect the noise level in terms of an audible hissing effect [12], which indicates the correctness and quality of the measuring systems.

4. CONCLUSION

The measurements presented in this paper for four cases illustrate how the position and method of installing HVAC system output units affect the noise level in the environment.

Special attention should be paid to the installation position of these systems in relation to surrounding outdoor and indoor areas. Before determining the position and method of installation of these noise sources, an appropriate design should be prepared to ensure that the environmental noise limit values are not exceeded.

Noise levels may increase later in the service life of HVAC system output units because of operating conditions or the failure of components subject to wear, such as fan bearings. It is therefore necessary to check noise levels periodically and carry out regular maintenance of the installations.

In many cases in practice, HVAC system output units have been installed without such designs. As a result, noise levels often exceed the limit values and cause disturbance in the surrounding environment from the start of operation, making additional noise protection measures necessary. These measures may be substantial, such as relocating the installations to carefully selected positions where the noise limit values will not be exceeded again, or installing appropriate sound-insulating enclosures with adequate airflow or sound barriers where site conditions permit.

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of output units of the HVAC systems in a chain of retail establishments of the same legal owner, according to his needs. The series of measurements included four reports from the Institute IMS ad from Belgrade. The authors would like to take this opportunity to thank the company GOMEX DOO, Miletićeva 27a from Zrenjanin, the client of the study.

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ASSESSMENT OF WHOLE-BODY VIBRATION EXPOSURE OF DUMP TRUCK DRIVERS IN A MINING COMPANY

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Abstract. *The technological processes associated with ore extraction are highly complex and include the transportation of extracted material from mining sites to processing facilities using continuous and discontinuous transport systems. Discontinuous systems involve various types of vehicle-based transport, with dump trucks being among the most commonly used means of ore haulage. Dump truck operators are exposed to various occupational hazards, including physical hazards such as noise and mechanical vibration. Particular attention should be given to whole-body vibration, which is transmitted to the operator through the vehicle seat during machinery operation and represents a significant occupational exposure factor. Risk assessment involves the systematic identification and evaluation of hazards and harmful factors to which workers are exposed, providing a basis for determining occupational risk and implementing appropriate occupational health and safety measures. Since physical hazards can be objectively quantified using specialised measurement equipment, measured exposure levels can be compared with permissible limit values established by applicable standards and legislation. This paper presents an analysis of whole-body vibration exposure and the associated occupational risk for dump truck operators in a mining company.*

Key words: *Whole-body vibration, Dump truck operator, Risk assessment, Preventive measures*

1. INTRODUCTION

Whole-body vibration (WBV) refers to mechanical vibration transmitted to the human body through the seat of a mobile work machine or through the feet when a worker is standing at the workplace. Occupational exposure to WBV is particularly common in off-road work environments, including agriculture, construction, and mining. From an occupational safety perspective, mining is classified as a high-risk industrial activity. The technological process of ore extraction encompasses not only the excavation of ore but also the transportation of extracted material to processing facilities. Both continuous and discontinuous transport systems are employed for this purpose. Continuous transport systems include conveyors, elevators, cableways, and screw conveyors, whereas discontinuous transport systems comprise cranes and various types of haulage vehicles, with dump trucks and load haul dump (LHD) vehicles being among the most

important. Mining and transportation machinery typically operates under highly complex and demanding conditions, characterised by dynamic work environments and the simultaneous presence of multiple occupational risk factors. Operators of mining machinery, including dump truck operators, may be exposed to a wide range of hazards and harmful factors, including [1-4]:

- Hazards associated with workplace characteristics: slippery surfaces when entering or exiting the vehicle cabin; contact with sharp edges of vehicle components; unfavorable microclimatic conditions and inadequate illumination inside the cabin; limited visibility from the operator's cabin; and other related hazards.
- Mechanical hazards: potential collisions with other moving vehicles; contact with other mining equipment operating at the site; and the risk of vehicle rollover.
- Fire hazards: the potential occurrence of fire in the vehicle cabin or engine compartment due to the presence of substantial quantities of hydraulic oil and fuel.
- Harmful agents: exposure to mechanical vibration, noise, exhaust gases, and airborne dust.
- Other harmful factors: prolonged sitting, fatigue, reduced concentration, monotonous work, overtime, night work, and shift work.

To ensure the effective implementation of occupational health and safety measures, a comprehensive risk assessment process is conducted, encompassing the identification of workplace hazards and harmful factors, the quantification and evaluation of the associated risks, and the development of appropriate occupational safety measures. The results of the risk assessment process are formally documented in a Risk Assessment Act [5]. This document also specifies the occupational safety measures to be implemented based on the identified type and level of risk, as well as its potential consequences for the safety and health of workers.

The focus of this study is the analysis of whole-body vibration (WBV) exposure among dump truck operators engaged in open-pit mining operations. Numerous studies

have investigated occupational exposure to whole-body vibration among dump truck operators and operators of other types of heavy machinery [6,7,8]. Based on relevant input parameters, including vehicle type and characteristics, operating conditions, measured WBV exposure levels, and the results of the occupational risk assessment, this study proposes appropriate preventive measures aimed at improving working conditions and protecting the health of workers exposed to mechanical vibration.

2. RISK ASSESSMENT OF WHOLE-BODY VIBRATION EXPOSURE

The principal European Union (EU) legal instrument governing the protection of workers from risks associated with exposure to mechanical vibration is Directive 2002/44/EC of the European Parliament and of the Council, commonly referred to as the “Vibration Directive” [9]. The Directive establishes minimum requirements for the protection of workers against health and safety risks arising from exposure to mechanical vibration in the workplace and distinguishes between two principal types of vibration exposure: hand-arm vibration (HAV) and whole-body vibration (WBV). For both types of exposure, the Directive establishes an exposure action value, above which employers are required to implement measures to control and reduce vibration-related risks, and an exposure limit value, which must not be exceeded.

Regarding whole-body vibration (WBV), Directive 2002/44/EC establishes the following exposure action and limit values:

- daily exposure action value (EAV) of 0.5 m/s²,
- daily exposure limit value (ELV) of 1.15 m/s².

These two established exposure values are expressed in terms of the daily vibration exposure value, $A(8)$, normalised to an eight-hour reference period.

In the Republic of Srpska, the legal framework is provided by the Law on Occupational Safety and Health and the Rulebook on Preventive Measures for Safe and Healthy Work During Exposure to Vibrations, published in the Official Gazette of the Republic of Srpska, No. 3/2018. In alignment with Directive 2002/44/EC, this national regulation defines the obligations of employers in implementing preventive measures to protect workers from risks arising, or likely to arise, from exposure to mechanical vibrations.

Risk assessment is generally conducted through the following steps [10]:

- Identification of hazards associated with workers' exposure to vibration;
- Assessment and evaluation of the risks arising from occupational exposure to vibration;
- Implementation of appropriate preventive and corrective measures.

2.1. Identification of the hazards associated with workers' exposure to vibration

In practice, work vehicles frequently operate on uneven terrain and poorly maintained roads. Under such operating conditions, the duration of exposure to mechanical

vibration may be prolonged, resulting in increased daily exposure to elevated vibration amplitudes and, in certain circumstances, to impulsive or shock-type vibrations. Inadequate maintenance of work equipment, as well as its improper use, may further contribute to an increased risk of adverse health effects associated with vibration exposure. Therefore, the use of a structured checklist comprising targeted questions can facilitate the systematic identification and assessment of occupational exposure to harmful vibration:

- Do you operate vehicles or machinery off-road?
- Do you operate vehicles or vibrating machinery for prolonged periods on a daily basis?
- Do you operate vehicles that are not suitable for the prevailing road or terrain conditions?
- Are you exposed to shocks, jolts, or sudden impacts during vehicle or machinery operation?
- Are you required to adopt awkward or sustained postures or perform manual handling tasks?
- Do machinery manufacturers provide warnings regarding the risk of exposure to whole-body vibration (WBV)?
- Have workers reported musculoskeletal disorders, particularly back disorders?

2.2. Assessment and Evaluation of Risks Associated with Vibration Exposure

Once a workplace has been identified as presenting a potential risk of adverse effects due to whole-body vibration (WBV), it is necessary to assess the level of vibration exposure using the daily vibration exposure value, $A(8)$, normalised to an eight-hour reference period. The assessment of vibration exposure can be performed using the following approaches:

- Direct measurement of vibration exposure: This approach requires specialised measurement equipment designed to measure mechanical vibrations transmitted to the human body. Although it provides objective exposure data, this method may involve considerable costs and requires appropriate technical expertise for measurement and data interpretation.
- Use of existing exposure data: Vibration exposure can also be assessed using data obtained from equipment catalogs, databases, or information provided by the equipment manufacturer, such as operating manuals and technical specifications.

Under the requirements of the Machinery Directive 2006/42/EC, machinery manufacturers are required to provide information on the vibration generated by machinery, including "measurement results under test conditions". Such information can be of significant importance during the procurement of work equipment, as it enables the preliminary comparison of different machines and facilitates the selection of equipment associated with lower vibration emission levels.

The parameters required for the calculation of daily vibration exposure, $A(8)$, include the frequency-weighted acceleration values measured along the three orthogonal axes (a_{wx} , a_{wy} , a_{wz}), and the corresponding duration of vibration exposure, T_{exp} . For an accurate assessment of

human exposure to mechanical vibration, precise determination of the exposure duration is as important as accurate measurement of the vibration magnitude. The exposure duration should be determined through detailed observation and analysis of the work process, using methods such as a stopwatch, video recording, or interviews with workers. Based on the measured vibration acceleration values and the corresponding exposure duration, the daily vibration exposure, $A(8)$, is calculated using the following equations [11]:

$$\begin{aligned} A_x(8) &= a_{wx} \cdot 1.4 \sqrt{\frac{T_{\text{exp}}}{T_0}}; \\ A_y(8) &= a_{wy} \cdot 1.4 \sqrt{\frac{T_{\text{exp}}}{T_0}}; \\ A_z(8) &= a_{wz} \sqrt{\frac{T_{\text{exp}}}{T_0}} \end{aligned} \quad (1)$$

The reference period T_0 is defined as 8 h, corresponding to a standard eight-hour working day. The highest of the three calculated values is taken as the daily vibration exposure value, $A(8)$:

$$A(8) = \max \{A_x(8), A_y(8), A_z(8)\} \quad (2)$$

2.3. Implementation of Appropriate Preventive and Corrective Measures

The employer is required to implement appropriate technological and organisational measures to reduce vibration-related risks when the daily vibration exposure action value or exposure limit value is exceeded. Such measures may include the implementation of alternative work processes, the selection of appropriate work equipment, and the reduction of both the duration and intensity of vibration exposure. Priority should be given to measures aimed at controlling or reducing vibration at its source, generally according to the following hierarchy:

- Technological measures: replacement of work equipment or selection of equipment that generates lower levels of vibration;
- Organisational measures: limiting the duration of exposure to high-intensity vibration, introducing regular work breaks, rotating workers during the work process, and implementing other appropriate organizational measures;
- Use of personal protective equipment (PPE).

Depending on the measured daily vibration exposure value, $A(8)$, the following measures shall be implemented:

- If $A(8) = 0.5 \text{ m/s}^2$: Workers shall be informed about the risks associated with exposure to mechanical vibration.
- If $A(8) > 0.5 \text{ m/s}^2$: A programme for reducing vibration exposure shall be developed and implemented, incorporating appropriate technical and organisational measures. The whole-body vibration reduction programme should include the following stages: determination of vibration exposure through direct measurement or the use of relevant databases; comparison of the measured exposure levels with the prescribed exposure

action and limit values; identification of the principal sources and causes of vibration; assessment of existing vehicles and equipment in comparison with available modern technologies; selection of appropriate control measures; prediction of the expected effectiveness of the selected measures; establishment of implementation timeframes; and verification of the achieved results.

- If $A(8) > 1.15 \text{ m/s}^2$: Immediate measures shall be taken to prevent further excessive exposure to whole-body vibration and to ensure appropriate periodic health surveillance of exposed workers.

The risk assessment should also take into account other factors that may adversely affect workers' health and that are directly or indirectly associated with exposure to vibration. These factors may include inadequate body posture while seated at the machine controls, prolonged sitting without sufficient opportunities to change position, improperly adjusted controls, and limited visibility requiring the worker to adopt awkward or constrained postures, as well as manual handling and lifting of loads. All of these factors may contribute to the development of musculoskeletal discomfort and, in particular, lower back pain. When combined with exposure to whole-body vibration, such ergonomic and physical stressors may further contribute to the development or aggravation of musculoskeletal symptoms and disorders.

3. CASE STUDY: WHOLE-BODY VIBRATION RISK ASSESSMENT AMONG DUMP TRUCK OPERATORS AT THE OMARSKA OPEN-PIT MINE

The objective of this study was to assess whole-body vibration (WBV) exposure among mining machinery operators during the transportation of tailings and valuable mineral raw materials at the Buvač open-pit mine, operated by ArcelorMittal Prijedor in Omarska, Prijedor, Fig. 1.



Fig. 1 Buvač open-pit mine, Omarska

Two types of Caterpillar dump trucks, shown in Fig. 2, were included in the study:

- CAT 777C, manufactured in 1980, with an unladen mass of 61,599 kg and a gross vehicle mass of 138,099 kg;
- CAT 775F, manufactured in 2010, with an unladen mass of 45,620 kg and a gross vehicle mass of 109,769 kg.

The two dump truck operators included in the study were male workers aged 35-40 years, with body masses of 78 kg and 90 kg and heights of 1.78 m and 1.84 m, respectively. Both vehicles were in operational condition at the time of the measurements. However, their operational status alone does not provide a comprehensive assessment of the condition of all vehicle components that may influence the generation and transmission of vibration. Particular consideration should be given to the condition and degree of wear of the tires, shock absorbers, and operator seats, as well as to the overall condition of the vehicle chassis, particularly in view of the age of the vehicles. For the purposes of this study, it was assumed that both vehicles were in satisfactory technical condition and suitable for the operating conditions characteristic of open-pit mining. Consequently, potential effects of inadequate vehicle maintenance or excessive component wear on the measured vibration exposure were not considered separately in the analysis.



Fig. 2 Caterpillar dumpers: CAT 777C and CAT 775F

3.1. Description of Work Tasks During an Eight-Hour Shift and Determination of Actual Vibration Exposure Duration

Dump trucks used in open-pit mining are classified as heavy mining machinery due to their substantial dimensions and high payload capacities. The unladen mass of the dump trucks considered in this study ranges from approximately 45 to 70 t, while their payload capacity ranges from approximately 60 t for newer models to 77 t for older models. Due to their size, mass, and operating characteristics, the use of dump trucks is subject to specific operational requirements, primarily related to the condition and design of haul roads within the open-pit mine, as well as prevailing weather conditions. Adverse weather conditions, particularly rainfall, may significantly affect operating safety by reducing road surface friction and increasing the risk of vehicle skidding and rollover.

When the required operating conditions are met, an eight-hour work shift can be divided into the following activities:

06:45–07:00: Arrival at the workplace, changing into work clothing, and exchanging relevant information with the operator from the previous shift.

07:00–07:10: Safety briefing conducted by the foreman, followed by the assignment and handover of work tasks for the shift.

07:10–07:15: Proceeding to the dump truck, conducting a visual inspection of the vehicle's operational condition, including the tires, oil level, braking system, and control systems, followed by engine start-up.

07:15–07:30: Refueling, if required, or traveling to the loading area within the open-pit mine.

07:30–09:30: Transportation of tailings and/or valuable mineral raw materials, including loading, hauling, unloading at the designated disposal or stockpile area, and returning to the loading unit.

09:30–10:30: Breakfast break.

10:30–14:30: Transportation of tailings and/or valuable mineral raw materials, including loading, hauling, unloading at the designated disposal or stockpile area, and returning to the loading unit.

Based on the work schedule presented above, the total effective operating time of the machine is initially estimated at approximately 6 hours per work shift. However, considering that the loading of raw material takes approximately 3 minutes per cycle and that the dump truck completes, on average, 10 loading cycles during a shift, a total of approximately 30 minutes is spent waiting for loading under the excavator (10×3 min.). Accordingly, the effective operating time during which the operator is exposed to vibration is estimated at approximately 5.5 hours per shift. This value is adopted as the reference daily vibration exposure duration, T_{exp} , for the subsequent calculation of whole-body vibration exposure.

3.2. Description of the Haul Route and Terrain Characteristics

The CAT 775F dump truck was assigned to transport tailings from the loading unit, located at an elevation of 30 m above sea level, to the tailings disposal site, located at an elevation of 187 m above sea level. Consequently, the dump truck had to negotiate an elevation gain of 157 m along the haul route. The route was frequently used by several other dump trucks, as shown in Fig. 3a. The road surface in the lower section of the route was uneven and rough. This section was not regularly graded due to the high frequency of mining equipment operating in the area, which limited the possibility of routine road maintenance.

The CAT 777C dump truck was assigned to transport tailings from the loading unit, located at an elevation of 90 m above sea level, to the disposal site, located at an elevation of 170 m above sea level, corresponding to an elevation gain of 80 m. In contrast to the CAT 775F route, the haul route used by the CAT 777C was less frequently trafficked, as shown in Fig. 3b. The haul roads in this area were systematically arranged and regularly maintained using a motor grader, resulting in more favourable road surface conditions.



Fig. 3 Haul routes: a) CAT 775F; b) CAT 777C

3.3. Measurement of Whole-Body Vibration

Whole-body vibration was measured using a human vibration analyzer (B&K 4447), in combination with a seat pad equipped with a triaxial accelerometer, which was positioned on the operator's seat of the dump truck, as shown in Fig. 4. Under normal operating conditions, the nominal duration of a work shift is eight hours; however, based on the analysis of the work process, the actual daily vibration exposure duration, T_{exp} , was determined to be 5.5 hours.



Fig. 4 Measurement equipment

The measured vibration acceleration values are presented in Table 1. The corresponding daily vibration exposure values, $A(8)$, were subsequently calculated using Eqs. (1) and (2).

Table 1 Measurement results [12]

Vehicle	RMS (m/s^2)			Daily vibration exposure $A(8)$ (m/s^2)
	X	Y	Z	
CAT 777C	0.2425	0.3327	0.5238	0.4343
CAT 775F	0.2839	0.3900	0.6651	0.5515

The experimental vibration measurements showed that the CAT 775F dump truck resulted in a daily whole-body vibration exposure value of $A(8) = 0.5515 \text{ m/s}^2$, which exceeds the prescribed Exposure Action Value (EAV) of 0.5 m/s^2 . In contrast, the CAT 777C dump truck resulted in an $A(8)$ value of 0.4343 m/s^2 , which is below the specified EAV, although it remains relatively close to the threshold value. These findings indicate that the exposure level associated with the CAT 775F requires the implementation of appropriate vibration control measures. In addition, preventive measures should be considered for both vehicle types to further reduce vibration exposure and support the long-term protection of operators' health.

4. CONCLUSION

A comparison of the operating conditions of the two analysed dump trucks indicates that differences in the working environment are primarily associated with the characteristics and condition of the haul routes. Uneven road surfaces, bumps, depressions, and other irregularities generate dynamic loads and vibrations in the vehicle, which are subsequently transmitted to the operator through the vehicle chassis and seat. Consequently, regular maintenance of haul routes, preparation of working areas, and proper maintenance of loading and disposal sites are important measures for reducing vibration exposure. Haul roads can be maintained using a motor grader, while the tailings disposal area can be maintained using a bulldozer. The latter can be used to redistribute deposited tailings and form a stable and sufficiently level platform for the safe arrival, maneuvering, and unloading of dump trucks. In the observed mining operation, siltstone, a by-product of the open-pit mining process, as well as limestone aggregate obtained from the nearby Drenovača quarry, are used for the preparation and maintenance of working and disposal areas. In addition to technical measures, appropriate organisational measures may contribute to reducing individual exposure to whole-body vibration. These include periodic rotation of operators, appropriate work-rest schedules, and adequate breaks during the work shift. Regular maintenance of machinery and haul roads, combined with appropriate organisational measures, can reduce vibration exposure and contribute to the prevention of adverse health effects associated with prolonged exposure to whole-body vibration.

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MITIGATION OF HAND-ARM AND WHOLE-BODY VIBRATION EXPOSURE AMONG CONSTRUCTION WORKERS

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Abstract. *In the construction sector, mechanical vibration exposure occurs routinely during the operation of heavy machinery (e.g., excavators, bulldozers, vibratory rollers, cranes, and other machinery) and hand-held power tools (e.g., pneumatic jackhammers, angle grinders, sanders, and chainsaws). Depending on the operational interface, workers absorb localised high-frequency energy via hand–arm vibration (HAV) or systemic low-frequency energy via whole-body vibration (WBV). This paper analyses the primary sources and mechanical propagation mechanisms of HAV and WBV in construction environments. Regulatory frameworks and standardisation directives—including European Directive 2002/44/EC, national rulebooks, and ISO standards (ISO 2631, ISO 7096, ISO 10819)—are detailed, outlining daily exposure action values (EAV) and exposure limit values (ELV). Furthermore, the etiology of occupational vibration disorders, such as Hand–Arm Vibration Syndrome (HAVS) and lumbar spine degeneration, is evaluated. Finally, an integrated hierarchy of risk mitigation controls encompassing engineering isolation, preventive maintenance, organisational work scheduling, and personal protective equipment (PPE) is synthesised.*

Key words: *Hand–Arm Vibration, Whole-Body Vibration, Construction Machinery, Occupational Safety, Hierarchy of Controls, Health Exposure Limits*

1. INTRODUCTION

Contemporary construction and civil engineering technologies depend significantly on powered machinery and mechanical systems to transmit substantial forces. This integration of mechanical and hydraulic power extends beyond heavy construction equipment into temporary structures, such as scaffolding and formwork, which have increasingly been transformed into mobile and mechanically operated systems [1]. Operating engineers (OEs) oversee the operation and maintenance of heavy construction equipment, such as cranes, bulldozers, front-end loaders, backhoes, and pavers. Their primary operational duties align with four major subdisciplines of civil and structural engineering [2]:

- Infrastructure Development: Constructing transport and water-management systems, including roadways, bridges, tunnels, and dams.
- Structural Erection: Assembling commercial, industrial, and power-generation facilities.

- Earthmoving and Paving: Executing site excavation, surface grading, and asphalt/concrete pavement installation or rehabilitation.
- Subsurface and Utility Engineering: Managing trenching, utility pipeline installation, drainage networks, and specialised operations such as controlled blasting [2].

However, the rapid mechanisation and automation of these workflows have heightened occupational health and safety concerns, prompting equipment manufacturers, regulatory bodies, and governmental institutions to prioritise hazard identification and risk mitigation [1]. Consequently, ensuring safe machinery operation demands both a technical understanding of power-transmission mechanics and the systematic identification, assessment, and control of physical, ergonomic, and occupational health hazards [1]. Minimising the incidence and severity of work-related injuries and occupational diseases ultimately relies on integrating proactive engineering controls, safety-oriented machine design, comprehensive operator training, and rigorous preventive management frameworks [1].

A major physical hazard inherent to heavy equipment operation is mechanical vibration — oscillations generated during machinery operation that propagate through the equipment to operators, adjacent structures, and the surrounding ground. Vibration intensity varies according to machinery design, operational state, maintenance condition, and the characteristics of the ground where work is performed. The primary sources of machinery-induced vibration include:

- Mechanical power systems, specifically engine operation and moving internal components;
- Impact and rotary working mechanisms;
- Dynamic ground-equipment interactions and terrain irregularities;
- Pressure fluctuations within hydraulic and pneumatic systems; and
- Direct force transmission during material compaction, drilling, and breaking operations.

To address these hazards, this study investigates engineering, organisational, behavioural, and personal protective interventions aimed at mitigating occupational

hand-arm vibration (HAV) and whole-body vibration (WBV) exposure among construction machinery operators and site personnel.

2. HAND-ARM AND WHOLE-BODY VIBRATION IN CONSTRUCTION

Construction workers are routinely exposed to mechanical vibration generated by hand-held tools and mobile construction machinery.

Occupational exposure to mechanical vibration generally manifests in two distinct operational modes [1]:

- **Hand-Arm Vibration (HAV):** Localised vibration transmitted through the hands and arms during the operation of hand-held power tools or mechanically vibrating structural interfaces [1].
- **Whole-Body Vibration (WBV):** Systemic vibration transmitted through the feet or supporting seat structures when operators stand or sit within vibrating environments, such as mobile construction machinery, transport trucks, or vibrating surfaces [1].

2.1. Hand-Arm vibration

Hand-Arm Vibration (HAV) primarily affects workers directly operating hand-held or hand-guided power tools (e.g., demolition hammers, scabblers, jackhammers, angle grinders, and chainsaws). HAV is characterised by localised high-frequency energy transferred through the hands and arms [1].

In field operations, HAV and ergonomic hazards frequently co-occur during labour-intensive tasks such as excavation, concrete placing, and structural finishing [3]. Manual excavation and backfilling expose workers to high mechanical loads while operating motorised tampers, which transmit severe vibration directly through the hands and forearms [3]. The associated risks are compounded by repetitive trench access, heavy manual soil movement, and the widespread use of non-ergonomic hand tools with minimal vibration attenuation [3]. Similarly, structural concrete work, including the operation of concrete pumps, motorised finishers, hand-held immersion vibrators, and powder-actuated tools, combines localised vibration exposure with forceful exertion and sustained non-ergonomic postures during manual raking and hand-trowelling [3].

2.2. Whole-Body Vibration

Whole-Body Vibration (WBV) primarily affects operators seated or standing within mobile heavy machinery, such as scrapers, bulldozers, excavators, loaders, skid steers, and haul equipment [1]. Mechanical energy in WBV manifests through three distinct physical mechanisms [1]:

- **Low-frequency, high-amplitude dynamics** stemming from interactions between the tyres or tracks of heavy machinery and unpaved, irregular site terrain;
- **High-frequency structural vibration** generated by internal combustion engines, hydraulic pumps,

and power-transmission gearboxes, transmitted through the chassis into the cabin interface; and

- **Transient dynamic shock loads** resulting from discrete impact events, including obstacle collisions, pothole traversals, and high-force soil-tool interactions during hydraulic breaking or pile-driving operations [1].

Figure 1 [1] and Table 1 [1] present common sources of equipment vibration during construction operations, including:

- Percussive and demolition equipment: pneumatic jackhammers, heavy demolition hammers, combi-hammers, and needle scalars;
- Surface preparation and masonry machinery: hammer-type scabblers, metal chipping hammers, and stone-working chisels;
- Power and rotary equipment: angle grinders, chainsaws, and random orbital sanders.

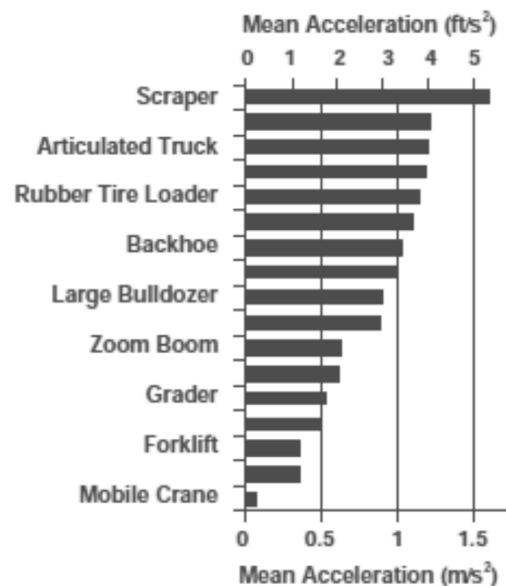


Fig. 1 Vibration of Common Equipment

Table 1 Vibration of Common Equipment

Powered Tool Type	Minimum [m/s ²]	Maximum [m/s ²]	Average [m/s ²]
Jackhammer	5	20	12
Demolition hammers	8	25	15
Hammer drills/combi hammers	8	25	9
Needle scalars	5	18	-
Scabblers (hammer type)	-	40	-
Angle grinders	4	8	-
Chipping hammers (metal)	-	-	18
Stone-working chisels	10	30	-
Chainsaws	-	-	6
Sanders (random orbital)	7	10	-

As detailed in Table 1, hammer-type scabblers produce peak accelerations up to 40 m/s². Vibration magnitudes for demolition hammers and hammer drills range between 8 m/s² and 25 m/s². Chainsaws typically produce vibration magnitudes of around 6 m/s² [1].

Table 2 provides a chronological overview of key empirical studies investigating HAV and WBV exposure among heavy equipment operators and construction workers, highlighting major operational determinants and clinical findings [4-11].

Table 2 Overview of vibration research among construction machinery operators and workers [2,4-13]

Study	Equipment	Exposure	Principal finding
Cann et al., 2003	67 construction machines	WBV	Several mobile machines exceeded recommended criteria
Kittusamy, Buchholz, 2004	Construction equipment operators	WBV	WBV and posture identified as important hazards
Coggins et al., 2010	289 construction/property workers; 264 tools and 158 vehicles	HAV/WBV	Tool age, work task and terrain affected exposure
Su et al., 2011	194 construction workers	HAV	High exposure associated with HAVS
Kurtz et al., 2012	Crane operators	HAV/WBV	Demonstrated simultaneous vibration exposures
McDowell et al., 2013 / NIOSH studies	Tool users	HAV	Strong dependence on tool/hand coupling
De la Hoz-Torres et al., 2022	Heavy-equipment drivers	WBV	Compared ISO 2631-1 and ISO 2631-5 approaches
Chaudhary et al., 2022	Heavy earthmoving operators	WBV	Transport-equipment operators had higher exposure and back-pain risk
Upadhyay et al., 2024	Dumper operators	WBV	Occupational and ergonomic factors were significant determinants
Sun et al., 2024	Construction/mining/metal/wood workers	HAV	Exposure-response relationship for upper-extremity disorders
Sun et al., 2025	Construction/mining/wood/metal workers	HAV	423 tools and 5,115 exposure segments quantified

The empirical investigation by Coggins et al. offers critical insight by concurrently evaluating hand-arm vibration (HAV) and whole-body vibration (WBV) within an active construction and property-management enterprise. Their findings revealed that tool age served as a primary determinant of HAV intensity, whereas WBV magnitude was predominantly dictated by work activity and terrain. These results underline the dual necessity of technical equipment maintenance and strategic work-organisation in exposure mitigation [5].

A recent major occupational health study in Germany established one of the largest empirical hand-arm vibration (HAV) datasets relevant to the construction sector. The investigation evaluated 423 power tools across 5,115 discrete exposure segments, reporting vibration magnitudes ranging from 0.8 to 65.2 m/s², with a median tool vibration magnitude of 14.2 m/s² [11].

Field measurements further demonstrate the severity of real-world exposures. Evaluating 20 hand-held tool types and 11 vehicle classes, Coggins et al. observed substantial variance in HAV across tool designs, whereas WBV was strongly influenced by task requirements and site terrain. Notably, maximum vibration intensities reached 13.3 m/s² for hand-held demolition hammers (HAV) and 5.81 m/s² for heavy excavators utilising rock-breaking attachments (WBV) [5].

Evaluating 67 individual heavy machinery units representing 14 functional categories, Cann et al. demonstrated that non-compliant WBV exposure is widespread across site operations. A broad range of mobile plant equipment – including wheel loaders, off-road dumpers, scrapers, skid-steers, backhoes, bulldozers, crawler loaders, and power trowels – exceeded health-based vibration dose value (VDV) threshold recommendations [4].

Ultimately, mechanical vibration represents a complex occupational hazard because overall human exposure is governed simultaneously by physical vector properties – magnitude, frequency spectrum, direction, and duration – and the biomechanical coupling between operator and machine. Field studies emphasise that real-world exposure levels depart substantially from nominal ratings due to site-specific variables, including equipment age, operational speed, task characteristics, surface topography, tool configuration, and operator habits. Demographic evidence highlights the vast population exposed to these risks: in the United States, approximately 540,000 operating engineers were subjected to whole-body vibration, with 90 % performing earthmoving and paving tasks (e.g., operating bulldozers, loaders, and excavators) and 10 % operating cranes [2]. Concurrently, in Germany, an estimated 1.5 to 2 million workers faced health-endangering levels of hand-arm vibration during routine industrial and construction activities [10].

3. HEALTH ISSUES DUE TO VIBRATIONS OF CONSTRUCTION MACHINERY AND EQUIPMENT

To effectively mitigate the physiological risks associated with hand-arm vibration (HAV) and whole-body vibration (WBV), a systematic hierarchy of

occupational health controls must be implemented across civil engineering projects.

Physiological Mechanisms and Etiology - Occupational exposure to mechanical vibration in heavy construction and civil engineering causes physiological damage to multiple body systems. The health consequences are dictated by exposure duration, acceleration magnitude, frequency spectrum, directional vectors, environmental conditions, individual susceptibility, and lifestyle factors (e.g., tobacco, alcohol, and pharmaceutical use) [3]. At the systemic level, sustained occupational vibration leads to acute and chronic health outcomes:

Somatic and Neurological Impairments: Fatigue, reduced work capacity, impaired concentration, diminished motor coordination, insomnia, headaches, and general neurological dysfunctions [1,3,6];

Cardiovascular and Autonomic Disruption: Systemic circulatory disorders, blood pressure variability, varicose veins, varicocele, and piles [1];

Gastrointestinal and Metabolic Disturbances: Organ shaking and intra-abdominal shear forces contributing to digestive disorders, appetite loss, and metabolic stress [1];

Musculoskeletal Degeneration: Accelerated wear of articular cartilage, chronic joint inflammation, and structural spinal lesions [1,2].

Hand-Arm Vibration Syndrome (HAVS) represents a major occupational disease affecting an estimated 1.45 million workers operating hand-held power tools according to the National Institute for Occupational Safety and Health (NIOSH) [3]. Historically referred to as "white finger disease" or "dead fingers" among stonecutters, HAVS encompasses three primary clinical manifestations [1,3,6]:

- **Vascular Disorders** – Prolonged use and forceful gripping of pneumatic or electric power tools induce vasospasms and microvascular occlusion in the digital capillaries, manifesting as secondary Raynaud's phenomenon [3,6]. Symptoms include episodic blanching ("white finger"), numbness, localised coldness, and loss of digital sensation [3]. Vascular attacks are significantly exacerbated by cold ambient working conditions [1,3]. In advanced cases, permanent circulatory impairment can progress to severe tissue ischemia and necrosis [3].
- **Neurological and Neurosensory Injuries** – Neurological pathology presents as progressive sensory loss, chronic paresthesia (tingling), and digital numbness [1,6]. Prolonged exposure directly damages peripheral nerves, leading to loss of tactile sensitivity, reduced spatial discrimination, diminished manual dexterity, and neurological disorders such as carpal tunnel syndrome [1,6]. A systematic review involving over 24,000 participants confirmed strong associations between occupational HAV and diverse hand disorders, with pooled odds ratios (OR) ranging from 1.35 to 3.43 depending on the clinical outcome [6].

- **Musculoskeletal Complications** – Biomechanically, HAV exposure combined with high grip forces causes severe strain on upper-extremity soft tissues, resulting in wrist tendinitis, tenosynovitis, and impaired grip strength [1,3].

Field evidence underscores the severity of HAV hazards on active construction sites. For instance, a study in Malaysia measured vibration magnitudes of 10.02 m/s² for concrete breakers, 7.72 m/s² for impact drills, and 5.29 m/s² for angle grinders, documenting an overall HAVS prevalence of 18 %, with significantly higher symptom prevalence in high-exposure cohorts [6].

For heavy machinery operators, whole-body vibration (WBV) interacts with prolonged static sitting, awkward posture, and vehicle shock loads to create high risks of severe musculoskeletal injuries – particularly affecting the lumbar spine [1,2].

4. REGULATORY FRAMEWORKS, EXPOSURE ACTION AND LIMIT VALUES, AND STANDARDIZATION DIRECTIVES

To mitigate the physiological hazards associated with mechanical vibration in heavy construction, international regulatory bodies and national statutory frameworks have established standardised threshold limit values and preventive management mandates. These regulations establish clear distinctions between hand-arm vibration (HAV) and whole-body vibration (WBV) based on transmission biomechanics, exposure action values (EAV), and exposure limit values (ELV).

Hand-arm vibration occurs when workers operate hand-held equipment such as pneumatic hammers, drills, grinders, and other vibrating power tools. Vibration is transmitted directly through the hands and can cause damage to blood vessels, nerves, and joints.

The daily exposure limit and action values specified in European Directive 2002/44/EC are:

- Daily exposure limit value (ELV): 5.0 m/s²;
- Daily exposure action value (EAV): 2.5 m/s².

If levels exceed these thresholds, work duration must be shortened and additional safety measures enforced.

Whole-body vibration occurs during the operation of machinery such as excavators, bulldozers, vibratory rollers, trucks, and loaders. The worker absorbs vibration through the seat, floor, or platform of the machine. Under European standards and occupational health regulations, daily exposure limit and action values for an 8-hour workday are set at:

- Daily exposure limit value (ELV): 1.15 m/s²;
- Daily exposure action value (EAV): 0.5 m/s².

When vibration levels exceed 0.5 m/s², employers must implement immediate exposure reduction measures.

Comprehensive occupational safety legislation, such as the Law on Safety and Health at Work and associated regulatory rulebooks, establishes mandatory employer obligations regarding physical workplace hazards. Employers must conduct vibration risk assessments, provide safe working conditions, organise regular vibration measurements and implement measures to protect employees [14].

The Rulebook on Preventive Measures for Safe and Healthy Work During Vibration Exposure details operational safety rules, including the following [15]:

- Daily exposure limit and action values;
- Vibration assessment and measurement protocols;
- Employer compliance obligations;
- Employee health surveillance programmes;
- Technical and organisational mitigation strategies.

It maintains explicit distinctions between whole-body vibration and hand-arm vibration.

The Rulebook on Preventive Measures for Safe and Healthy Work at the Workplace defines mandatory conditions for workplaces and machinery to mitigate physical hazards, including vibration [16].

The Rulebook on Procedures for Inspection and Testing of Work Equipment mandates regular technical inspections and verification of construction machinery, minimising excess vibration caused by mechanical defects [17].

Technical standards applied alongside legal acts include:

- ISO standards for vibration measurement,
- SRPS standards in acoustics and vibration, and
- European Standards (EN ISO).

Common standards cover vibration testing on machinery, human exposure evaluation, and structural impact assessments.

ISO 2631 (“Mechanical vibration and shock – Evaluation of human exposure to whole-body vibration”) gives permissible exposure limits as a function of acceleration, frequency and length of exposure (1 min–24 h). As expected, lower accelerations are required at frequencies between 4 and 8 Hz because the human body is most sensitive to WBV at these frequencies. For example, a piece of equipment that vibrates at a frequency between 4 and 8 Hz should not produce vertical accelerations above 0.315 m/s^2 over an 8-hour day. If the operator works only 4 hours per day, the acceleration may reach 0.54 m/s^2 [1].

Guidelines established by the International Organization for Standardization (ISO 2631) suggest that for seven hours of continuous work, the magnitude of vibration should not exceed 0.8 m/s^2 [1].

ISO 7096 provides a laboratory method for evaluating the effectiveness of operator-seat suspension on earthmoving machinery.

5. MITIGATION

Mitigating vibration-induced injuries in construction environments requires a structured hierarchy of controls. Relying on any single method is rarely sufficient; rather, effective risk reduction depends on combining primary engineering controls, active and preventive maintenance, organisational and managerial controls, and personal protective equipment (PPE).

Technical measures at the source represent the most effective defence against both whole-body vibration (WBV) and hand-arm vibration (HAV) [1,3]. Primary engineering interventions aim to isolate vibration energy

before it reaches the operator's musculoskeletal system [1,3].

Technical Isolation for Hand-Arm Vibration (HAV):

- **Vibration-Damping Handles and Couplings:** Modern power tools incorporate flexible anti-vibration couplings and handle suspensions that decouple tool vibrations from the operator's grip [3].
- **Ergonomic Handle Geometry:** Optimising handle contours reduces the required grip force [3]. Lower grip force decreases dynamic coupling between the hand and tool, significantly lowering vibration transmission into the musculoskeletal structures of the hand and arm [3].
- **Impact Shock Attenuation:** Specialised handles on percussive machinery (e.g., pneumatic hammers and breakers) feature integrated damping mechanisms designed to absorb mechanical shock impulses [3].

Technical Isolation for Whole-Body Vibration (WBV): Preventing trauma from WBV relies on three primary engineering strategies:

- **Source/Haul-Road Optimization:** Lowering vehicle speeds and maintaining smooth, well-designed working surfaces and haul routes to reduce shock input [1].
- **Cabin Suspension Isolation:** Installing elastic mounts, springs, and pneumatic shock absorbers between the main chassis and the operator cabin [1,3].
- **Advanced Seat Suspension Systems:** Equipping cabs with adjustable, vibration-damping seats that feature lumbar and cervical spine support [1,3]. These advanced seating systems effectively attenuate chassis oscillations and low-frequency shocks while providing essential acoustic isolation [3].

Preventive Equipment Maintenance. Maintaining machinery in sound technical condition is critical, as worn parts and defects significantly increase vibration intensity.

Coggins et al. identified tool age as a primary predictor of elevated HAV magnitudes, underscoring routine maintenance as an essential occupational health intervention rather than merely an operational activity [5]. Comprehensive maintenance protocols must systematically include [4]:

- bearing inspection;
- replacement of worn components;
- balancing;
- lubrication;
- inspection of impact mechanisms;
- replacement of damaged handles;
- inspection of cutting tools;
- calibration and vibration monitoring where appropriate.

Maintenance should consequently be considered an occupational safety intervention, not solely an engineering or production activity.

Organisational Measures. When engineering controls cannot completely eliminate mechanical vibration,

managerial interventions limit worker exposure duration and modify operational behaviours [1]:

- Exposure-Time Management: Enforcing strict daily shift limits, establishing mandatory rest intervals, and implementing job rotation schemes across non-vibrating tasks.
- Hazard Designation: Formally identifying, labelling, and establishing designated "vibration hazard areas" and "vibration hazard tools" to restrict exposure of unauthorised personnel.
- Vibration Monitoring and Records: Conducting periodic quantitative exposure assessments and maintaining standardised monitoring records to verify compliance with EAV [1].
- Operator Training Programmes – educating workers on safe operating techniques [1]. Operator education should specifically focus on:
 - Operating at appropriate speeds and selecting optimal transport routes.
 - Avoiding unnecessary structural impacts and aggressive tool coupling.
 - Adjusting operator seats to match body weight and stature.
 - Monitoring equipment for unusual vibration signatures.

Personal Protective Equipment (PPE) – serves as the final line of defence within the risk-mitigation hierarchy.

- Hand-Arm Vibration PPE – anti-vibration gloves (compliant with standards such as ISO 10819) incorporate viscoelastic material layers designed to attenuate high-frequency energy. Field evaluations among sheet-metal operators demonstrated that anti-vibration gloves achieved absolute vibration reductions ranging from 3.07 m/s² to 5.56 m/s² compared to a bare-handed baseline condition of 12.91 m/s².
- Whole-body vibration PPE – elastomeric insoles, shock-absorbing work boots, padded cab mats, and supportive belts offer supplementary damping against transient shocks.

To achieve maximum protection, control measures should follow a strict hierarchy of implementation – low-vibration tool selection, engineering controls, preventive maintenance, exposure-time reduction, and personal protective equipment.

6. CONCLUSION

Vibration from construction machinery represents a significant risk factor in the construction industry. It affects worker health, structural stability, and environmental quality. Regular monitoring, proper protective measures, and technically sound equipment are essential for ensuring safe working conditions.

Permissible vibration limits serve to safeguard workers' health and surrounding structures. Systematic measurement, equipment maintenance, and protective measures minimise the risks of occupational illnesses and structural damage.

Legal standards and rulebooks covering construction machinery vibration are essential to workplace safety and

environmental protection. Strict compliance guarantees controlled vibration levels, healthier working environments, and safer equipment operation.

Protecting against construction machinery vibrations is essential for preserving worker health, building integrity, and environmental quality. Combining technical, organisational, and protective strategies yields safer, higher-quality construction operations. The most effective construction-site strategy is therefore an integrated hierarchy of controls, rather than dependence on a single measure.

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EXPERIMENTAL ASSESSMENT OF CREW VIBRATION EXPOSURE DURING ARTILLERY FIRING

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Abstract. *The vibrations generated during the firing of artillery systems have a significant impact on crew safety and occupational health. This paper presents the results of experimental measurements and analyses of shock-induced vibrations in artillery systems equipped with 125 mm guns, as well as 122 mm and 155 mm gun-howitzers, in accordance with the relevant standards and Directive 2002/44/EC. The results indicate that the maximum recorded shock accelerations reached approximately 8.55 g, while the measured vibration levels remained within the permissible limits for short-term exposure. The findings also show that vibration intensity depends not only on the weapon calibre but also on the structural characteristics of the artillery system. The use of appropriate personal protective equipment is therefore recommended to further reduce the risk associated with crew exposure to shock-induced vibrations.*

Key words: *Vibrations, Measurements, Assessment, Risks, Crew*

1. INTRODUCTION

The firing of projectiles from artillery weapons integrated into various combat platforms generates extremely high levels of vibration. The crew is directly exposed to the shock loads produced during the firing event. During the design phase, particular attention is devoted to minimising and damping these unavoidable physical phenomena in order to enhance crew protection. When new combat systems are introduced into military service, the so-called “human factors” of the platforms are also evaluated. These include ergonomic suitability and compatibility with the capabilities and limitations of the operators, i.e., the crew members. Such an approach contributes both to improved crew protection and to the optimisation of the system's operational performance.

The measurement and analysis of vibrations generated during the firing of artillery systems make it possible to

determine their intensity and characteristics, which is essential for assessing their effects on both the crew and the structural durability of the platform. The accuracy and reliability of the obtained data depend on several factors. The first is the proper selection of measurement locations, i.e., the identification of representative measurement points on the platform that accurately reflect the effects of vibrations on the crew and the system structure. The second factor is the use of appropriate measurement instrumentation, which must be calibrated, capable of covering the expected vibration range, and sufficiently sensitive to detect the short-duration shock impulses generated during firing. The third factor is the experience and expertise of the personnel responsible for conducting the measurements and processing the acquired data, since reliable analysis requires an understanding of frequency components, spectral distribution, and vibration damping characteristics. Together, these factors provide reliable information on vibration intensity, which can be used to optimise crew protection, improve ergonomics, and extend the service life of the system.

In Serbia, there is no single reference source that clearly defines tolerance thresholds and permissible crew exposure limits for the risks associated with artillery firing, nor are there universally accepted criteria for their assessment. A similar situation exists in many other countries due to the specific nature of military activities and the limited availability of publicly accessible data.

Although there are no military standards that directly define crew exposure limits during artillery firing, the international ISO standards (ISO 2631-1 to ISO 2631-5) provide technical guidelines for the evaluation of whole-body vibration, including frequency weighting, exposure assessment methods, and measurement procedures [1]. These standards are primarily applied in industrial and civilian environments to assess comfort, fatigue, and the potential adverse effects of vibration on the human body.

Nevertheless, they may also serve as valuable reference guidelines in military applications when comparing vibration levels associated with transport and combat platforms [2].

In addition, the internationally recognized ISO 5349 standard (Parts 1 and 2) specifies methods for measuring and evaluating hand-transmitted vibration and is widely applied to hand-held tools, machinery, and equipment [3]. Furthermore, Directive 2002/44/EC of the European Parliament and of the Council on the minimum health and safety requirements regarding workers' exposure to vibration establishes exposure criteria and reference values that are frequently adopted in vibration assessment and research [4].

In addition to these international standards, Serbia has national legislation governing occupational exposure to vibration. However, these regulations are primarily intended for civilian workplaces and do not directly address the specific exposure conditions associated with artillery firing. The Regulation on Preventive Measures for Safe and Healthy Work under Vibration Exposure provides requirements for assessing whole-body vibration exposure and is applied mainly within the context of occupational ergonomics and workplace safety [5].

The scientific literature also includes studies investigating the effects of vibration on personnel in the context of military systems. These studies relate the frequency, intensity, and duration of vibration exposure to the physiological responses of the human body, providing a basis for the development of local assessment criteria or the refinement of existing standards. The findings indicate that certain vibration components may be either negligible or dominant depending on the measurement methodology [6], and that different evaluation methods (e.g., VDV versus RMS) may yield substantially different estimates of exposure risk [7]. Other studies have established a direct relationship between vibration intensity and the potential risk of spinal injury and other adverse health effects [8]. Furthermore, it has been demonstrated that the overall vibration magnitude alone is insufficient for assessing health effects; the frequency content of the vibration is equally important, as it determines the actual biomechanical response and physiological impact on the crew [2].

Nevertheless, several aspects and criteria for the assessment of shock-induced vibrations from the perspective of their effects on humans have been addressed in the literature and may serve as a basis for vibration evaluation and risk assessment [9–12].

The aim of this study is to present a comparative analysis and assessment of the vibration parameters generated by artillery guns of different calibres mounted on different platforms. Experimental measurements were carried out under field test conditions on platforms equipped with 122 mm, 125 mm, and 155 mm artillery systems. To minimise measurement uncertainty, each parameter was measured at least three times at the same location, and the arithmetic mean of the recorded values was adopted as the representative result. Based on the assessment criteria proposed in previous studies [9–12], the measured shock-induced vibrations of the investigated systems were evaluated.

2. METHODOLOGY AND VIBRATION MEASUREMENT PROCEDURE

2.1. Theoretical background

The term “human vibration” refers to mechanical vibrations transmitted to the human body that may cause adverse effects on health, safety, and human performance. The assessment of vibration exposure in the workplace within the European Union is regulated by Directive 2002/44/EC of the European Parliament and of the Council [4], which defines minimum requirements for the protection of workers against risks arising from exposure to mechanical vibration. The methodology for vibration measurement and exposure assessment is based on the international standard ISO 2631-1: Mechanical vibration and shock – Evaluation of human exposure to whole-body vibration [1].

The Directive distinguishes between two main categories of vibration:

- Whole-body vibration (WBV) – vibrations transmitted to the entire human body through the seat, floor, or foot support. This type of vibration is characteristic of vehicles, construction and industrial machinery, as well as combat vehicles.
- Hand-arm vibration (HAV) – vibrations transmitted to the hands and arms during the operation of hand-held tools or the manipulation of machine control elements.

Since the subject of this study is the analysis of vibrations to which the crew of self-propelled artillery systems is exposed, only whole-body vibrations (WBV) are considered.

The primary indicator for assessing whole-body vibration exposure is the daily vibration exposure value, i.e., the equivalent frequency-weighted acceleration normalised to a reference period of eight hours. According to ISO 2631-1, this value is determined using the following expression:

$$A(8) = a_w \cdot \sqrt{\frac{T}{T_0}} \quad (1)$$

where $A(8)$ represents the daily vibration exposure normalised to an eight-hour working day (m/s^2), a_w is the root mean square (RMS) value of the frequency-weighted acceleration, which represents the input parameter for exposure assessment (m/s^2), T is the actual vibration exposure duration, and $T_0 = 8 \text{ h}$ is the reference exposure duration.

Whole-body vibrations are measured along three mutually perpendicular axes corresponding to the anatomical directions of the human body: the longitudinal (x), lateral (y), and vertical (z) axes. For each axis, the frequency-weighted root mean square acceleration values a_{wx} , a_{wy} and a_{wz} are determined. In some analyses, the overall vibration magnitude is expressed by the resultant acceleration:

$$a_v = \sqrt{(k_x \cdot a_{wx})^2 + (k_y \cdot a_{wy})^2 + (k_z \cdot a_{wz})^2} \quad (2)$$

where a_{wx} , a_{wy} and a_{wz} represent the acceleration components along the corresponding axes, while k_x , k_y and

k_z are weighting factors that account for the different sensitivity of the human body to vibration in individual directions. For whole-body vibration, the standard specifies the values $k_x = k_y = 1.4$ and $k_z = 1.0$.

The resultant acceleration a_v represents a single measure of the overall vibration intensity when all three measurement directions are considered simultaneously. However, for the official assessment of daily vibration exposure according to ISO 2631-1 and Directive 2002/44/EC, the highest weighted value among the components $1.4a_{wx}$, $1.4a_{wy}$ and a_{wz} is most commonly used. This value corresponds to the parameter a_w in Eq. (1).

In cases where a person is exposed to vibrations of different intensities during multiple time intervals within a working day, the daily vibration exposure for each axis is determined by summing the energy contributions of individual exposure periods according to the following expression:

$$A_l(8) = k_l \sqrt{\frac{\sum_{i=1}^n a_{wl,i}^2 T_i}{T_0}} \quad (3)$$

where $A_l(8)$ represents the daily vibration exposure normalised to an eight-hour working day for the l -th axis, k_l is the weighting factor for the l -th axis, $a_{wl,i}$ represents the frequency-weighted RMS acceleration value along the l -th axis during the i -th exposure interval, T_i is the duration of the i -th exposure interval, n is the total number of exposure intervals, and $T_0 = 8$ h is the reference exposure duration.

In addition to the RMS acceleration value, ISO 2631-1 also introduces the Vibration Dose Value (VDV), which is intended for the assessment of vibrations with pronounced shock or impulsive characteristics. It is defined by the following expression:

$$VDV = \left(\int_0^T a^4(t) dt \right)^{1/4} \quad (4)$$

where $a(t)$ represents the instantaneous frequency-weighted acceleration value, and T is the total measurement duration.

Unlike RMS acceleration, which represents the mean energy content of vibration, VDV is based on the fourth power of the instantaneous acceleration value, making it significantly more sensitive to short-duration peak events. This characteristic makes VDV particularly suitable for the analysis of vibrations generated during artillery firing, where high-intensity transient impulses occur and may be underestimated if the assessment is based solely on RMS acceleration values.

For the purpose of evaluating the obtained results, the reference values defined in Directive 2002/44/EC were used. These values specify the action and exposure limit values for whole-body vibration. Although these limits are primarily intended for civilian occupational environments, they were adopted in this study as reference criteria for assessing potential risks in military applications.

2.2. Measurement methodology

The intensity of vibration can be described in terms of displacement, velocity, or acceleration, with acceleration being the most commonly used primary measurement quantity for evaluating the effects of vibration on humans. According to ISO 2631-1, vibration exposure assessment is based on the frequency-weighted root mean square (RMS) acceleration and, in cases where vibrations exhibit pronounced impulsive characteristics, on the Vibration Dose Value (VDV). However, in this study, the maximum (peak) acceleration value was also analysed, considering that the firing of an artillery system represents a short-duration, high-intensity impulsive excitation. The analysis of peak acceleration values provides direct insight into the maximum dynamic loading experienced by the crew during firing, while RMS acceleration and VDV provide the basis for assessing overall exposure in accordance with applicable standards.

Acceleration transducers (accelerometers) measure acceleration in a single direction; therefore, spatial vibration analysis requires the use of three single-axis accelerometers positioned along mutually orthogonal directions or a single triaxial accelerometer. In previous studies, vibration measurements were most frequently performed only in the dominant direction (typically along the z -axis), in accordance with the standards and measurement capabilities available at the time. Current standards and European regulations require vibration measurements along three mutually perpendicular axes, with the coordinate system defined relative to the human body or the hand-arm system, depending on the vibration transmission path [13].

For the measurement of vibrations to which the crew is exposed, a measurement chain consisting of three single-axis A131 accelerometers (manufactured by Connection Technology Center) was used. The accelerometers were positioned along the x , y , and z axes at the designated measurement location on the system and connected to a multichannel acquisition system, NetdB12 (manufactured by 01dB-Metavib), as shown in Fig. 1.



Fig. 1 Elements of the measuring chain:
1 – accelerometers, 2 – NetdB12, 3 – computer with appropriate software

The coordinate system was defined relative to the operator's body, with the z -axis corresponding to the vertical direction (up-down), the x -axis to the longitudinal direction (forward-backward), and the y -axis to the lateral direction (right-left), as illustrated in Fig. 2.

Based on the measured acceleration values along three mutually orthogonal axes, characteristic vibration parameters can be determined, including peak acceleration values, root mean square (RMS) values, resultant acceleration, and daily vibration exposure indicators. The obtained results provide a basis for assessing the loads to which the crew is exposed during the operation of artillery systems [13,14], in accordance with the methodology defined by ISO 2631-1 and Directive 2002/44/EC.

Figure 2 shows the coordinate system used for vibration measurements, defined with respect to the body of the operator–gunner, with the x , y , and z axes corresponding to the directions of vibration acceleration.

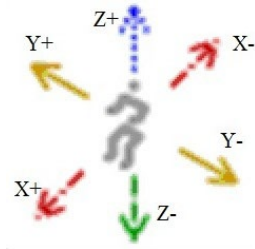


Fig. 2 x , y , and z axes of the coordinate system relative to the operator-gunner

For the purpose of the measurements, an anthropomorphic test dummy of appropriate mass was used to simulate the operator-gunner. The accelerometers were positioned at predefined measurement points on the operator's seat, the cabin floor, and the body of the test dummy in order to record shock-induced vibrations relevant for the assessment of crew exposure (Fig. 3).

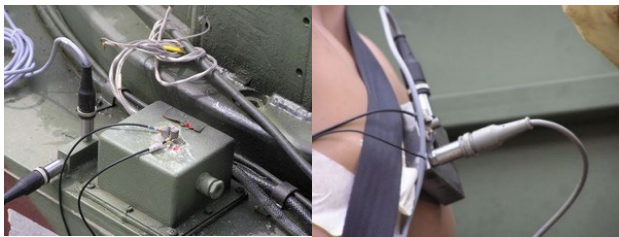


Fig. 3 Examples of shock-induced vibration measurement locations: on the cabin floor (left) and on the body of the operator simulated by an anthropomorphic dummy of appropriate mass (right)

3. RESULTS OF SHOCK ACCELERATION-VIBRATION MEASUREMENTS

Shock acceleration measurements following artillery firing were performed on systems equipped with 122 mm, 125 mm, and 155 mm calibre guns.

For the three-axis accelerometer measurement location, the gunner's seat was selected for the systems equipped with a 125 mm gun and a 122 mm howitzer. For the 125 mm system, an additional measurement was performed on the turret. The seat was loaded with a mass of 50 kg to simulate the operator's load. The firing tests were conducted using instantaneous high-explosive projectiles (IHEP) of the corresponding calibres, i.e., 125 mm and 122 mm.

The acceleration response curve generated during firing with 122 mm IHEP ammunition is presented in Fig. 4.

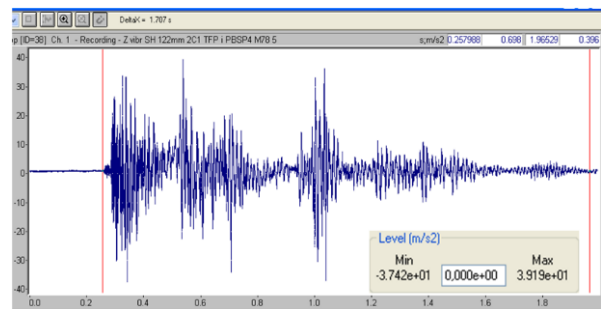


Fig. 4 Acceleration response curve generated during firing of the 122 mm gun-howitzer

For the 155 mm gun-howitzer, the three-axis accelerometer measurement location was selected at the commander's seat, which was loaded with a mass of 50 kg. The acceleration response curves generated during firing, measured along all three axes, are presented in Figs. 5, 6, and 7.

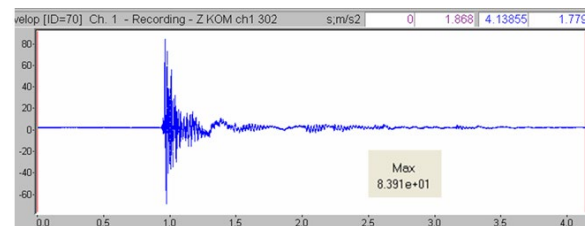


Fig. 5 z -axis shock acceleration response at the commander's seat during 155 mm gun-howitzer firing

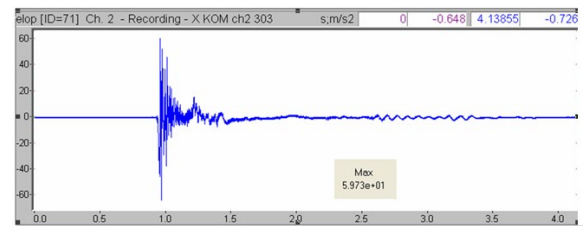


Fig. 6 x -axis shock acceleration response at the commander's seat during 155 mm gun-howitzer firing

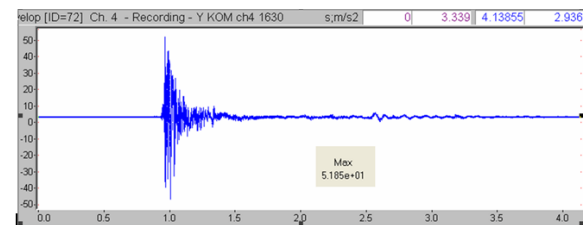


Fig. 7 y -axis shock acceleration response at the commander's seat during 155 mm gun-howitzer firing

Based on Figs. 5, 6, and 7, which present the time histories of shock acceleration (vibration) along all three axes, it can be observed that firing produces a highly impulsive excitation of the structure, followed by damped oscillations that gradually decrease over time. It can be concluded that the highest dynamic loading occurs along the z -axis, while the x -axis exhibits the longest duration of

oscillations. This indicates that the structural response varies depending on the direction of excitation, which is important considering the influence of vibrations on the crew and the design of the commander's seat.

The results of the shock-induced vibration measurements are presented in Table 1. For the 122 mm howitzer, five measurements were performed, while three additional measurements were performed on the turret of the 125 mm system. As previously stated, the peak level of shock acceleration–vibration was analysed, i.e., the maximum measured value (peak), expressed in m/s^2 .

Table 1 Results of shock vibration measurements for the tested systems

Firing sequence number	Test systems	Measurement point	Peak shock acceleration level (m/s ²)					
			z +/-	Mean value z+/-	x +/-	Mean value x+/-	y +/-	Mean value y+/-
1	125 mm gun (IHEP)	gunner's seat	4.00 / 3.15	+3.38 / -3.14	2.79 / 2.44	+3.14 / -2.86	3.57 / 4.09	+3.49 / -3.30
2		on the turret	3.72 / 4.05		4.03 / 2.78		3.38 / 3.21	
3			2.59 / 2.74		2.92 / 3.28		3.83 / 2.91	
4			3.20 / 2.61		2.80 / 2.95		3.17 / 2.98	
1	122 mm howitzer (IHEP)	gunner's seat	3.57 / 3.50	+3.79 / -3.51	2.34 / 2.04	+2.51 / -2.41	2.74 / 4.00	+3.11 / -3.72
2			3.75 / 3.60		2.51 / 2.45		3.62 / 3.60	
3			4.14 / 3.19		2.67 / 2.38		2.93 / 3.62	
4			3.75 / 3.36		2.34 / 2.99		3.18 / 3.25	
5			3.74 / 3.92		2.71 / 2.17		3.09 / 4.14	
1	155 mm howitzer	commander's seat	8.55		5.97		5.19	

4. VIBRATION ASSESSMENT CRITERIA AND ANALYSIS OF MEASUREMENT RESULTS

As stated in the introductory section of this paper, there are currently no regulations that define in detail the criteria for assessing the effects of shock-induced vibrations on the crew during artillery firing. In order to establish a criterion applicable for evaluating vibration levels from the perspective of their harmful effects on operators and crew members, the available relevant literature was reviewed.

Based on the relevant references [9–12], for vibration exposure durations up to 0.1 s, the following permissible acceleration values can be identified:

- in the lateral direction: approximately 8 g [9] and approximately 14 g [11];
- in the vertical direction: approximately 11 g [10], up to approximately 20 g [9], or up to approximately 22 g in the positive direction and approximately 11 g in the negative direction [11];
- in the direction perpendicular to the chest: approximately 15 g [9] and up to approximately 32 g [11];
- without a defined direction of action: up to approximately 26 g [12].

The referenced literature defines criteria based on acceleration expressed in units of g (where $1 \text{ g} = 9.81 \text{ m/s}^2$), which can also be considered applicable to the systems investigated in this study. Based on the adopted parameters, approximate limit values for permissible vibration levels can be defined as follows:

- up to 11 g along the z-axis,
- up to 15 g along the x-axis,
- up to 8 g along the y-axis.

The above values refer to short-duration vibration exposure lasting up to 0.1 s.

The analysis of the measured shock-induced vibration values (Table 1) showed that the maximum values reached 4.09 g along the y-axis for the system equipped with a 125 mm gun, 4.14 g along the y-axis for the system equipped with a 122 mm gun-howitzer, and 8.55 g along the z-axis for the system equipped with a 155 mm gun-howitzer. By comparing these results with the defined criteria, it can be concluded that the recorded shock-induced vibrations during firing are within the permissible limits.

5. CONCLUSION

The assessment of crew exposure to shock-induced vibrations generated during artillery firing was performed in accordance with relevant scientific literature and the criteria defined in the Regulation of the Republic of Serbia on preventive measures for safe and healthy work during exposure to vibrations, which is based on the requirements of the European Union Directive 2002/44/EC.

By applying appropriate measurement equipment for the investigation of vibration effects on the crew and by comparing the obtained results with applicable standards, the European Directive, and existing research, specific indicators related to human safety and health protection against physical hazards were obtained, representing the primary objective of this study.

The analysis of the measured values at selected measurement locations on systems equipped with a 125 mm gun, a 122 mm gun-howitzer, and a 155 mm gun-howitzer showed that the maximum shock accelerations during firing reached approximately 8.55 g. Based on a comparative analysis with criteria reported in the literature for similar systems and test conditions, it can be concluded that the observed vibrations do not exhibit pronounced harmful characteristics; however, the need for appropriate protective equipment cannot be excluded.

Furthermore, it can be concluded that the level of shock-induced vibrations is not determined solely by the

weapon calibre, but also by the design characteristics of the system itself, including the suspension system, stabilisation system, and other structural parameters.

The presented measurement methodology can also be applied to other types of military systems, with the aim of achieving compliance with European standards in the fields of comfort, safety, and occupational health protection.

Since this investigation did not include all factors that may influence the measurement results, there remains potential for further development of the methodology, particularly regarding different test conditions. Future research should include an expanded analysis of the influence of various ammunition types and propellant charge variations.

Based on a larger number of conducted tests and analyses, it is recommended to develop a dedicated regulation defining criteria for the assessment of vibration effects on crews for specific military systems and calibres currently in service.

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CASE STUDY: OCCUPATIONAL NOISE AND WHOLE-BODY VIBRATION EXPOSURE OF BACKHOE-LOADER OPERATOR DURING EXPLORATORY MINING

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Abstract. *An occupational noise and whole-body vibration assessment was conducted at an exploratory mining site at the workplace position of a backhoe-loader operator. The exposure to noise and whole-body vibration in the working environment was determined and evaluated in accordance with national regulations and relevant standards. The results were compared with data provided by the equipment manufacturer and guidelines from relevant literature.*

Key words: *ISO 9612, ISO 2631, Occupational noise exposure, Whole-body vibration, Earthmoving machinery*

1. INTRODUCTION

At the planned location of the future gold mine in the Homolje Mountains, occupational noise and whole-body vibration assessment was conducted for workers engaged in exploration preparations. This paper presents an assessment for the workplace position of a backhoe-loader operator and compares it with the data provided in the manufacturer's technical documentation and technical guidelines.



Fig. 1 Backhoe-loader

2. METHODOLOGY

Measurements were made by using a four-channel 20 kHz signal analyser including a sound level meter (including the microphone and associated cables meeting IEC 61672-1, class 1) and a vibration meter (including a seat accelerometer with a sensitivity of 100 mV/g for whole-body measurements meeting ISO 8041). Noise

assessment was carried out according to the Regulation on preventive measures for health and safety (Off. J. RS. 2011, 96) [1] and ISO 9612 [2], and vibration according to the Regulation on preventive measures for health and safety (Off. J. RS. 2011, 93) [3] and ISO 2631-1 [4].

As for assessment of noise, ISO 9612 Strategy 1 [2] – Task-based measurement was chosen as appropriate. The work performed during the day is analysed and split up into a number of representative tasks, and for each task separate measurements of sound pressure level are taken.

Typically, a backhoe operator at an exploratory mining site clears access paths, digs test trenches, and moves bulk earth materials to support geological sampling and site setup. With a combined construction machine such as a backhoe-loader, the loudest noise occurs during tasks that require maximum engine performance under high load and hydraulic resistance, that is, during heavy excavation and hard surface work, often over 90 – 95 dBA outside the cab during the backhoe digging task in hard, stony ground. High noise occurs during heavy material loading and pushing, medium during transport of materials and driving and the least noise during idling.

At the measurement site, the activities included clearing access paths and moving bulk earth materials. The backhoe-loader where measurements were performed was a CAT 434F. It is a modern-generation loader, sound-insulated and featuring quiet engine operation. Tests were conducted with the doors and windows closed.

In Fig. 2, the graph shows the time-domain waveform of the noise measured inside the loader's cab. The recording distinguishes between a steady noise component (associated with moving bulk earth materials) and a fluctuating noise component (associated with clearing access paths).

One twenty-minute measurement was performed in a cycle that includes these activities at the site and was considered as one task on the basis of which the exposure assessment for the entire working day was performed. Based on this, a nominal nine-hour day has been defined, comprising a first break of 30 minutes and a second break of 10 minutes, with 8 hours and 20 minutes allocated to the task itself. The breaks are considered quiet periods free from vibration.

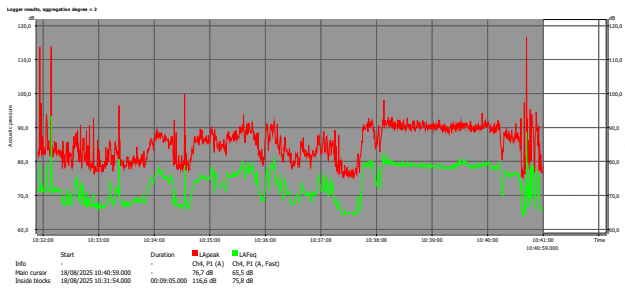


Fig. 2 Time-domain record of noise

At the same time, whole-body vibration was measured using a seat accelerometer. As for assessment of whole-body vibration, ISO 2631-1 basic evaluation method was used, and as for the additional evaluation of vibration when the basic evaluation method is not sufficient, the fourth power vibration dose method [4,5]. A graphical representation of the time-domain waveform of the whole-body vibration is shown in Fig. 3.

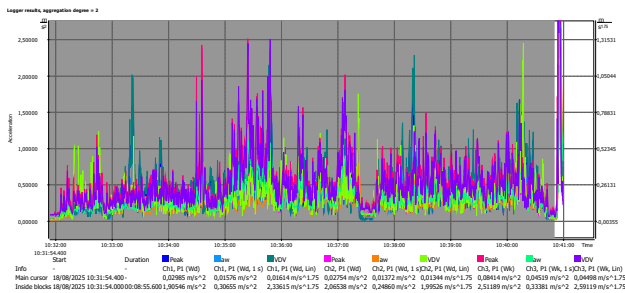


Fig. 3 Time-domain record of whole-body vibration

The backhoe-loader operator is also exposed to hand-arm vibration, which was not included in this assessment.

As for comparing test results with limit values, noise was assessed both for the risk of hearing damage and for the level range underneath the given risk of hearing damage and whole-body vibration with respect to health.

The limit values for assessing the risk of hearing damage are given in Table 1. As for level range underneath the given risk of hearing damage limit values are specified by the Regulation [1] and VDI 2058-3 [6].

Table 1 Limit values for assessing the risk of hearing damage

Quantity	Regulation [1]	
	Daily noise exposure level, $L_{EX,8h}$	C-peak sound pressure level, $L_{p,Cpeak}$
Lower exposure action value	80 dB	135 dB
Upper exposure action value	83 dB	136 dB
Exposure limit value	85 dB	137 dB

The regulation requires conditions for distraction-free work, while the VDI standard addresses the assessment of noise loads based on the activity performed. For the job of backhoe-loader operator, both the Regulation (covering work involving demanding control and operator cabins) and VDI 2058-3 (covering work characterized by

psychomotor – fine-motor – activity, such as eye-hand coordination) specify a limit value of 70 dB.

As for assessment of whole-body vibration with respect to health, limit values are specified by the Regulation [3]. For basic evaluation method it gives daily exposure action value of 0.5 m/s^2 standardised to an eight-hour reference period and daily exposure limit value of 1.15 m/s^2 standardised to an eight-hour reference period. As for the additional evaluation of vibration Directive [7] gives daily dose action value of $9.1 \text{ m/s}^{1.75}$ and daily dose limit value of $21 \text{ m/s}^{1.75}$.

3. MEASUREMENT RESULTS

An equivalent noise level of 75.8 dB was measured, resulting in a daily noise exposure of 76.0 dB with an associated expanded uncertainty for a one-sided coverage probability of 95 % ($k = 1.65$) of at least 2.0 dB, considering only the standard uncertainties due to the instrumentation used and related to microphone position [2]. The highest equivalent noise level of 79 dB was recorded during the steady noise segment (see Fig. 2). The measured C-peak sound pressure level was 117.9 dB with an expanded measurement uncertainty of 4.0 dB [2].

Regarding whole-body vibration, the measurement results are presented in Table 2.

Table 2 Whole-body vibration measurement results

Axis	Frequency weighting	Multiplying factor, k	Weighted rms accelerations, $k \cdot a_w \text{ [m/s}^2\text{]}$	Peak value, $A_w \text{ [m/s}^2\text{]}$	Crest factor
x	W_d	1.4	0.31	1.91	6.2
y	W_d	1.4	0.25	2.07	8.3
z	W_k	1.0	0.33	2.51	7.5

Based on the measurement results, the daily exposure level $A(8)$ is 0.44 m/s^2 with an associated expanded uncertainty for coverage probability of 95 % ($k = 2$) of 0.30 m/s^2 , considering only the standard uncertainty due to accelerometer calibration and the instrumentation accuracy [8]. The results of the additional evaluation method used are presented in Table 3.

Table 3 The additional evaluation method measurement results

Axis	VDV $[\text{m/s}^{1.75}]$	VDV/ $(a_w T^{1/4})$
x	1.35	1.58
y	1.15	1.67
z	1.50	1.61

Based on the measurement results, the vibration dose value (VDV) is $9.0 \text{ m/s}^{1.75}$.

4. DISCUSSION

Regarding the comparison with limit values for assessing the risk of hearing damage, noise exposure levels do not exceed the limit values. If we compare this with the data provided by the manufacturer [9], we see that the declared values for the work cycle have not been exceeded

either. The manufacturer's declared value is 78 dB(A) for the operating cycle, with the cabin doors and windows closed, that does not significantly exceed even the highest measured equivalent noise level of 79 dB(A). Regarding limit values for the level range underneath the given risk of hearing damage limit value is exceeded, and in this respect, the noise can be considered disruptive to work.

Regarding whole-body vibration, the limit values are not exceeded. Vibration exposure is close to the daily standardised exposure action value of 0.5 m/s^2 . As for the additional evaluation of vibration used, crest factors are below or equal to 9 (see Table 2), so the basic evaluation method is normally sufficient. However, for vibrations along the x - and y -axes, the value is close to 9. Value of 1.75 for ratio used for comparison of basic and additional methods of evaluation, $\text{VDV}/(a_w T^{1/4})$ is not exceeded (Table 3) but very close along the y -axis. For the vibration dose value limit values are not exceeded yet daily dose is very close to action value.

When comparing the measurement results with the manufacturer's data [9], the discrepancy is much greater than that observed for the noise levels. The manufacturer provides data based on the ISO/TR 25398 [10] and emphasizes that it is not possible to state precise vibration levels for the machine, noting that expected levels can only be roughly estimated using this data. The data are presented in Table 4. While the values along the x - and y -axes (Table 2) almost coincide with those given in Table 4 and fall within the measurement uncertainty of 0.15 m/s^2 and the standard deviations from Table 4, respectively, the value measured along the z -axis far exceeds the estimated value. This highlights the importance of field measurements under actual conditions for assessing health impacts, as estimates based on manufacturer data and guidelines from relevant literature underestimate actual exposure.

Table 4 Equivalent vibration values of whole-body vibration emission of earth-moving machinery [10]

Machine family	Loader
Machine kind	Wheel backhoe loader
Typical operating condition	Excavating
Weighted r.m.s. accelerations, $1.4 \cdot a_{wx} [\text{m/s}^2]$	0.28
Weighted r.m.s. accelerations, $1.4 \cdot a_{wy} [\text{m/s}^2]$	0.26
Weighted r.m.s. accelerations, $a_{wz} [\text{m/s}^2]$	0.2
Standard deviation, $s_x [\text{m/s}^2]$	0.09
Standard deviation, $s_y [\text{m/s}^2]$	0.16
Standard deviation, $s_z [\text{m/s}^2]$	0.06

5. CONCLUSION

During occupational noise and whole-body vibration assessment conducted at an exploratory mining site at the workplace position of a backhoe-loader operator, noise levels were recorded that, while posing no health risk, exceeded values considered disruptive for the type of work performed. Whole-body vibration levels did not exceed limit values but were very close to the lower action levels for the basic assessment method and the additional vibration evaluation method used. A comparison with the manufacturer's noise data showed good agreement, falling within the range of measurement uncertainty. However, comparing whole-body vibration levels against manufacturer data and relevant literature guidelines indicated that relying on such information – without conducting measurements under actual operating conditions – would result in an underestimation of actual exposure.

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CALCULATION OF OCCUPATIONAL NOISE LEVELS FROM AMMUNITION FIRING BASED ON TESTING IN ACCORDANCE WITH SRPS EN ISO 9612

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Abstract. *In the production of weapons and ammunition, personnel involved in testing products in the shooting range are directly exposed to gunshot noise. Testing by direct measurement at the test shooter's workplace requires special equipment. In this paper, the determination of noise exposure and evaluation were performed based on measurements at positions near the shooter's position using equipment that meets the requirements of SRPS EN ISO 9612 and the calculation of occupational noise levels based on measurements. Based on the approximation model and measurement technique, the measurement uncertainty for the test results was estimated and the results were compared with the results of reference tests from the literature.*

Key words: *Gunshot noise, Occupational noise exposure, ISO 9612, Measurement uncertainty, Noise level calculation*

1. INTRODUCTION

Noise measurements form part of periodic assessments of working environment conditions. Periodic testing of working environment conditions in Serbia is carried out at intervals not exceeding three years, in accordance with occupational health and safety regulations [1]. The tests cover microclimate (temperature, humidity, air velocity), chemical and physical hazards (noise, vibrations, radiation), biological hazards and lighting. As part of these regular assessments, workplace noise levels are measured during weapon firing in both the arms and ammunition manufacturing industries.

Since measuring noise at the shooter's position requires specialized equipment [2,3], this paper presents a method for estimating the noise level at the shooter's position based on measurements taken with standard equipment at a greater distance.

The results of the calculations presented in this paper may also be applicable to workplaces within the police and military.

1.1. Standard measuring equipment

Testing and evaluation according to the Regulation on preventive measures for health and safety (Off. J. RS. 2011, 96) [4] require equipment compliant with ISO 9612 [5]. Sound level meters, including the microphone and associated cables, shall meet the requirements of IEC 61672-1, for Class 1 or Class 2 instruments. Class 1 sound

level meters require a minimum dynamic range of 60 dB for their linear operating range, though typical commercial Class 1 instruments provide wider measurement ranges (such as 25 dB to 140 dB for high-level peaks). Most basic commercial Class 2 meters provide a total measurement range of 30 dB to 130 dB. Personal sound exposure meters, including the microphone and cable, shall meet the requirements specified in IEC 61252. The standard specifies performance criteria that generally correspond to an A-weighted sound pressure level range from at least 67 dB to 137 dB, though commercial dosimeters built to this standard typically provide wider measurement ranges of 55 dB to 140 dB(A).

1.2. Specialized equipment required

Published measurements indicate peak noise levels at the shooter's position ranging from approximately 154 to 181.3 dB [2,3,6], exceeding the specified measurement ranges of standard equipment. Furthermore, when selecting equipment for the required test, the directivity and dimensions of the microphone must be taken into account [3]. In the frequency domain, the short acoustic impulse corresponds to a broadband signal with substantial high-frequency content. It is important that the microphone be small compared to the wavelength of the target sound at high frequencies. When the diameter becomes comparable to the wavelength, the microphone can locally disturb the sound field (see Fig. 1). This will result in an increased sound pressure gradient in front of the microphone and can lead to the diaphragm sticking to the backplate mechanism. This can be avoided by pointing the microphone perpendicular to the direction of sound propagation, as shown in Fig. 2. Here, the dimensions of the microphone become significant. At higher frequencies, when the acoustic wavelength becomes comparable to the microphone diaphragm diameter, spatial variations in pressure across the diaphragm can cause partial signal cancellation. Microphones with diameters of 1/8 inch and 1/4 inch are used for such measurements, whereas standard equipment typically uses a 1/2-inch microphone.

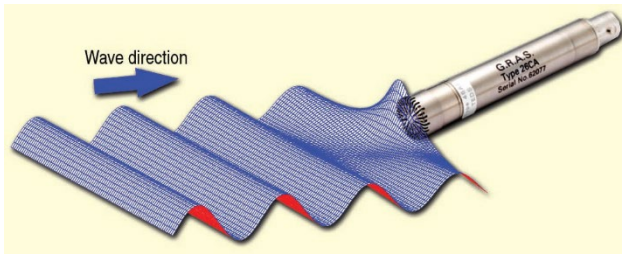


Fig. 1 Diffraction around the microphone when pointed toward the direction of propagation of the sound field [2]

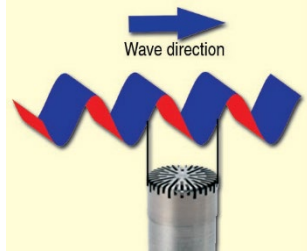


Fig. 2 Perpendicular direction: signal cancellation when the wavelength is on the order of the microphone's dimensions [2]

2. METHODOLOGY

Measurements were performed using an SV104A personal sound exposure meter equipped with an ST 104CIS MEMS microphone in a 1/2-inch housing. The instrument has a frequency range of 20 Hz to 10 kHz. Comparison of the instrument specifications with the requirements outlined in Section 1 indicated that the equipment was unsuitable for direct measurements at the shooter's position. Such measurements could produce unreliable data and potentially damage the instrument. Measurements were therefore performed at a greater distance, with the aim of keeping the recorded levels within the instrument's operating range. Noise levels at the shooter's position were subsequently estimated by calculation. Figure 3 shows the time-domain waveform recorded at a distance of 7.8 m from the source. Even at this distance, the reported peak level of 144.1 dB exceeded the stated measurement range.

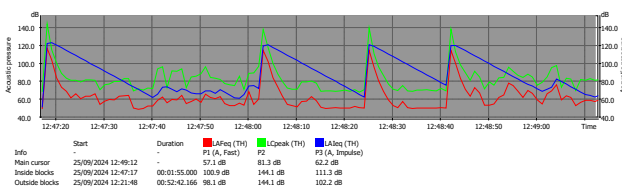


Fig. 3 Time-domain record of shooting noise

2.1. Measurement setup

The firing range comprised an indoor firing room from which the shooter aimed at an outdoor target through an opening in the wall. The room contained doors and windows. Rather than being positioned 0.1 – 0.4 m from the entrance to the external ear canal beside the more exposed ear, the microphone was positioned outside the room at the shooter's height, with the door open. It was oriented perpendicular to the direction of sound

propagation. Wherever possible, an unobstructed path was maintained between the source and the microphone (Fig. 4). Figure 5 illustrates the alternative arrangement, in which the source was not directly opposite the measurement position.

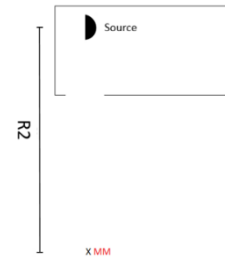


Fig. 4 The source is directly opposite the measurement position. R2 is the direct perpendicular distance from the source to the microphone.

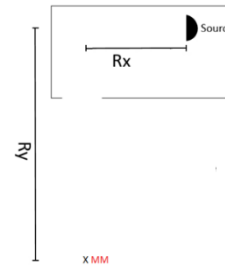


Fig. 5 The source is not directly opposite the measurement position. Rx is the direct perpendicular distance from the source to the door and Ry is the direct perpendicular distance from the source to the microphone.

2.2. Calculation method

The formula used to calculate sound attenuation with distance from a point source is [7]:

$$L_p(R2) = L_p(R1) - 20 \log_{10} \left(\frac{R2}{R1} \right) \quad (1)$$

where $L_p(R1)$ is the sound pressure level at the worker's position, $L_p(R2)$ is the measured sound pressure level at distance R2, R1 is the distance from the source to the worker's ear (20 cm), and R2 is the distance from the source to the microphone. The equation describes sound attenuation under free-field conditions. For indoor measurements, the influence of the room's acoustic properties must also be considered.

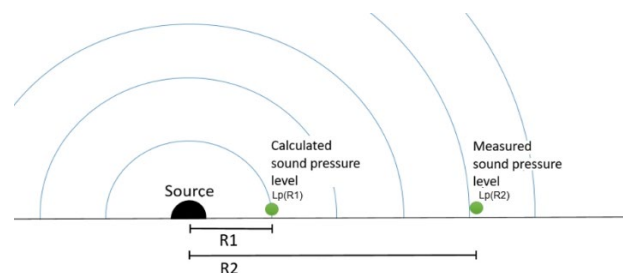


Fig. 6 Positions of the noise source, the shooter's location for which the calculation is performed, and the microphone (adapted from [7])

2.2.1. Source directly opposite the measurement position

When the source is directly opposite the measurement position (Fig. 4), it is sufficient to consider the influence of the environment. The sound pressure level can be determined using the equation:

$$L_p(R1) = L_p(R1)' - K_{2A} \quad (2)$$

where $L_p(R1)$ is the sound pressure level at a distance $R1$ under free-field conditions, $L_p(R1)'$ is the corresponding level inside the room, and K_{2A} is the environmental correction factor [8]. The environmental correction factor is calculated using the following equation:

$$K_{2A} = 10 \log_{10} \left[1 + 4 \frac{S}{A} \right] \quad (3)$$

where S is the area of the spherical surface enclosing the source at a distance $R1$, and A is the absorption area of the room, determined by the following equation:

$$A = \bar{\alpha} \cdot S_V \quad (4)$$

where S_V is the total area of the room's boundary surfaces and $\bar{\alpha}$ is the average sound absorption coefficient. For the room investigated, its approximate value ranges from 0.05 to 0.1. A coefficient of 0.05 corresponds to a nearly empty room with smooth, rigid walls, while 0.1 corresponds to a partially empty room with smooth walls. For the room investigated, the calculated environmental correction factor, K_{2A} , ranges from 0.61 to 1.15 dB. Comparing these values to the standard uncertainty of 1.5 dB for a Class 2 instrument [5], the correction can be neglected as it does not significantly affect the result.

2.2.2. Source not directly opposite the measurement position

When the source is not directly opposite the measurement position (Fig. 5), additional assumptions must be introduced. In this case, the distance $R2$ is calculated using the equation:

$$R2 = R_X + R_Y \quad (5)$$

Here, the sound at the measurement point is not direct sound, but sound reflected from the room's wall surfaces. The approximation assumes that a low absorption coefficient corresponds to a high reflection coefficient:

$$\alpha^2 + r^2 = 1 \quad (6)$$

In this instance, the reflected sound is further reduced by the portion absorbed within the room (K_{2A}); consequently, the result should be corrected by $2 K_{2A}$ – a factor that can be disregarded, however, given the instrument's uncertainty of 1.5 dB.

2.3. Influence of measurement setup in the frequency domain

The initial calculations used an average sound absorption coefficient, $\bar{\alpha}$, without accounting for its frequency dependence. However, gunshot noise is broadband and contains substantial high-frequency energy.

A frequency-dependent assessment therefore requires consideration of both surface absorption and sound absorption in air, which influence the room's equivalent absorption area, A , and the environmental correction factor, K_{2A} .

Using a single average absorption coefficient may not adequately represent the acoustic conditions in individual frequency bands. If a more detailed calculation is performed, that takes frequencies into account, when calculating the parameters at a specific high frequency such as 8000 Hz, two opposing physical phenomena occur that fundamentally alter the values of α and K_{2A} compared to the broad averages. Surface absorption α drops while smooth, rigid surfaces become highly reflective mirrors for short high-frequency wavelengths, causing the wall absorption coefficient to drop significantly below the average α value of 0.10 or 0.05. Air attenuation A spikes, as at high frequencies, air absorption dominates the room acoustics. The air itself absorbs a massive amount of sound energy, which drastically expands the room's total equivalent absorption area, yielding total values, i.e. in 8000 Hz octave-band for $\alpha = 0.07$ and for $K_{2A} = 4.4$ dB (average α value of 0.10), and 0.07 and 1.0 dB (average α value of 0.05) respectively. If, for a typical measurement (see Fig. 3), we conduct an octave analysis and apply octave-band corrections, then reconstruct the corrected noise level and carry out the calculation described in Section 2.2, the resulting overall environmental correction factor, K_{2A} , ranges from 1.6 (for average α value of 0.05) to 2.4 dB (for average α value of 0.10) for the specific room where the testing was conducted.

2.4. Influence of measurement setup in the time domain

Regarding the time domain, the change in operating conditions necessitated by the measurement setup may become significant. Specifically, ammunition is normally fired in an enclosed space; with the doors open, the absorption area (A) changes, thereby altering the reverberation time:

$$T_{60} = \frac{0.161V}{A} \quad (7)$$

where V is the room volume. Although this does not affect the calculated maximum noise levels (L_{AFmax}), it can influence the overall equivalent noise level and the daily noise exposure level ($L_{EX,8h}$). For the room investigated, the calculated reverberation time decreased from 1.91 s with the door closed to 1.79 s with the door open. The corresponding difference in equivalent sound pressure level was 0.3 dB and was treated as negligible in the subsequent calculations.

2.5. Uncertainty budget

The contributions to measurement uncertainty, considering the standard uncertainties due to the instrumentation used, related to microphone position, calculation method, frequency-dependent variations in absorption and measurement setup influence on reverberation time, are presented in Table 1. According to ISO 9612, the standard uncertainty associated with

microphone positioning is 1 dB. Regarding imprecision in determining the measurement position (0.1 – 0.4 m), the formula for sound attenuation with distance from a point source yields a difference of 0.4 dB for the measured values, which complies with the standard's requirements. The range of uncertainty values arising from the calculations is attributable to the range of values assumed for α and the treatment of the frequency dependence of α . If this uncertainty is also taken into account and corrections are not applied, a higher value should be used for calculating measurement uncertainty.

Table 1 Uncertainty budget

Microphone positioning	1.0 dB
Instrumentation used	1.5 dB
Calculation 2.2.1	0.61 – 1.15 dB/ 1.6 – 2.4 dB
Calculation 2.2.2	2·(0.61 – 1.15) dB/ 2·(1.6 – 2.4) dB
Time domain influence	0.3 dB

3. MEASUREMENT RESULTS

Testing was conducted in two firing ranges: one used for single-shot ammunition testing, where the setup involved the source positioned not directly opposite the measurement point (see Fig. 5), and another used for burst-fire testing, where the setup involved the source positioned directly opposite the measurement point (see Fig. 4). The results are presented in Tables 2-4. The parameters evaluated were the maximum sound pressure level (L_{AFmax}), the equivalent noise level for the measurement interval (L_{AFeq}), and the peak C-weighted sound pressure level (L_{Cpeak}). Noise levels at the shooter's position were calculated without applying the corrections specified in Section 2; however, these corrections were factored into the measurement uncertainty. The associated expanded uncertainty corresponds to a one-sided 95 % confidence interval ($k = 1.65$).

Table 2 Measurement and calculation results for L_{AFmax}

Shooting range	Ammunition type	Ammunition firing method	Measured value [dB]	Calculated value at shooter's	U [dB]
1	9 × 19 mm	single-shot	110.0	138.3	3.9
1	7.62 × 39 mm	single-shot	114.2	152.5	3.9
1	12.7 × 108 mm	single-shot	120.2	152.0	3.9
2	7.62 × 39 mm	burst-fire	120.6	148.9	3.0

Table 3 Measurement and calculation results for L_{AFeq}

Shooting range	Ammunition type	Ammunition firing method	Measured value [dB]	Calculated value at shooter's	U [dB]
1	9 × 19 mm	single-shot	96.7	125.0	3.9
1	7.62 × 39 mm	single-shot	95.1	123.4	3.9
1	12.7 × 108 mm	single-shot	100.9	132.7	3.9
2	7.62 × 39 mm	burst-fire	117.7	146.0	3.0

Table 4 Measurement and calculation results for L_{Cpeak}

Shooting range	Ammunition type	Ammunition firing method	Measured value [dB]	Calculated value at shooter's	U [dB]
1	9 × 19 mm	single-shot	139.0	167.3	4.7
1	7.62 × 39 mm	single-shot	130.8	159.1	4.7
1	12.7 × 108 mm	single-shot	144.1	175.9	4.7
2	7.62 × 39 mm	burst-fire	143.1	171.4	4.0

Based on the calculated values, occupational noise exposure was determined in accordance with ISO 9612 Strategy 1 – Task-based measurement. The work performed during the day is analysed and divided into representative tasks, and for each task separate measurements of sound pressure level are taken. For the shooter in Range 1, the tasks involve firing various types of ammunition in single-shot mode for a total daily duration of 6 hours, while for the shooter in Range 2, the task involves firing ammunition in burst mode for a duration of 6 hours. The shooter in shooting range 1 is subject to a daily A-weighted noise exposure level of 127.8 dB with an associated expanded uncertainty of 3.9 dB if the uncertainty in duration is omitted, and the shooter in shooting range 2 to exposure level of 144.8 dB with uncertainty of 3.0 dB. Limit values are provided in Table 5.

Table 5 Limit values for assessing the risk of hearing damage [4]

Quantity	Regulation [4]	
	Daily noise exposure level, $L_{EX,8h}$	C-peak sound pressure level, $L_{p,Cpeak}$
Lower exposure action value	80 dB	135 dB
Upper exposure action value	83 dB	136 dB
Exposure limit value	85 dB	137 dB

4. DISCUSSION

Regarding the comparison with limit values for assessing the risk of hearing damage, noise exposure levels exceed all limit values, except in the case of single-shot firing of 7.62 × 39 mm ammunition, where the peak C-weighted level does not exceed the limit values.

The calculated levels were compared with published measurements. Brueck et al. [3] report peak A-weighted levels of 154.7 to 171.4 dB, while Rasmussen et al. [2] report 153.2 to 184.2 dB. Using an indirect measurement method at distances similar to those in this study (7 m), Matys et al. [6] report peak C-weighted levels ranging from 157.9 to 181.3 dB and maximum sound pressure levels ranging from 132.9 to 157.9 dB. A comparison with the results presented in Tables 2 and 4 shows that the range of results yielded by the method presented here falls entirely within the range of the cited results.

The method has several limitations: while it is straightforward for measuring noise levels with the source directly opposite the measurement position (see Fig. 4), the indirect measurement of reflected waves (see Fig. 5) is heavily influenced by room characteristics. Furthermore, the method relies on the assumption of negligible absorption, making it practically applicable only to the scenario shown here, a room with smooth, rigid walls. An increase in the absorption coefficient increases the total measurement uncertainty, as evidenced by a comparison of the measurement uncertainty in the test results for firing ranges 1 and 2 (Tables 2-4). A second drawback stems from the characteristic frequency spectrum of the gunshot and the occurrence of increased absorption at higher frequencies. An analysis of the contributions of the average $\bar{\alpha}$ value and the frequency-specific α (Section 2.3) reveals that accounting for this effect would reduce the measurement uncertainty of the calculation component (Table 1) from 2.4 to 1.15 dB, thereby also reducing the expanded measurement uncertainty from 3.9 to 2.4 dB.

5. CONCLUSION

The paper presents a measurement method and corresponding calculation procedure for the indirect determination of noise at the shooter's position, identifying sources of uncertainty and ways to reduce total uncertainty through correction factors. The results align well with existing literature for both direct and indirect measurements, and for the specific case presented, applying corrections was found to be unnecessary given the estimated expanded measurement uncertainty. Direct noise measurement at the shooter's position requires specialized, high-cost equipment and can present technical challenges

during active testing. The indirect method verified in this study offers an alternative for evaluating occupational noise exposure levels without compromising data precision. Future research could focus on testing the proposed approximation model alongside a direct measurement method to further verify the model and identify additional potential sources of uncertainty.

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CASE STUDY: OCCUPATIONAL NOISE EXPOSURE IN A BANK CASH PROCESSING CENTRE

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Abstract. Noise testing and occupational noise exposure assessment were performed across 27 locations within the main, regional, and local cash processing centres of three banks. Conducted periodically over a 12-year period in accordance with national regulations and relevant standards, the study evaluated noise levels both for the level range above the given risk of hearing damage and for the one underneath the risk considered to be disruptive to work. This paper compares the longitudinal results of these assessments and variations to highlight occupational health risks and environmental trends in specific banking environments.

Key words: ISO 9612, DIN 45645-2, Occupational noise exposure, Hearing damage risk, Disruptive noise assessment, Cash processing centre

while with the entry into force of ISO 9612:2009 and the new Regulation, rating the levels for noise damaging to hearing was abandoned, while rating levels were retained in the assessment of noise for the level range underneath the given risk of hearing damage [10,11].

2.1. Assessment procedure and the limit values

In the noise rating procedure, the assessment level, L_r , is derived directly from the A-weighted equivalent continuous sound level, L_{pAeq} , determined for the activity, and the corresponding adjustments for impulsive, K_I , and for tonal content, K_T [2,3,7]:

$$L_r = L_{pAeq} + K_I + K_T \quad (1)$$

Here "impulse"-weighted equivalent continuous sound level L_{pAeq} (time weighting "I") is retained as a measure to describe impulsivity in noise immersion during an activity or part-time work. The difference is in surcharge to account for the increased disturbance effect of impulsive noises. Until 2016, according to the Regulation [2] and ISO 9612:1997, a minimum of 2 decibels of difference between the "impulse"-weighted equivalent continuous sound level and A-weighted equivalent continuous sound level was required to characterize noise as impulsive, and later, according to DIN 45645-2, 3 decibels. An overview of the differences in noise rating is given in Table 1.

Table 1 Surcharge to account for the increased disturbance effect of impulsive noises

Surcharge K_I	Regulation [1], ISO 9612:1997	DIN 45645-2
$K_I = 0$ dB, if	$L_{pAeq} - L_{pAeq} < 2$ dB	$L_{pAeq} - L_{pAeq} < 3$ dB
$K_I = L_{pAeq} - L_{pAeq}$, if	$L_{pAeq} - L_{pAeq} > 2$ dB	$L_{pAeq} - L_{pAeq} = 3$ to 6 dB
$K_I = 6$ dB, if	-	$L_{pAeq} - L_{pAeq} > 6$ dB

As for comparing test results with limit values, an overview of the limit values used, both for assessing the risk of hearing damage and for assessing the level range underneath the given risk of hearing damage, is given in Tables 2 and 3. Table 3 gives values for tasks relevant to work in the bank cash processing centre.

1. INTRODUCTION

As part of the periodic testing of working environment conditions, noise in count rooms of bank cash processing centres was periodically tested, both in large central and regional and local cash processing centres in several banks in Serbia.

Periodic testing of working environment conditions in Serbia is carried out every 3 years at most, in accordance with occupational health and safety regulations [1]. The tests cover microclimate (temperature, humidity, air flow velocity), chemical and physical hazards (noise, vibrations, radiation), biological hazards and lighting. Here, an overview of noise test results for multiple banks over a longer period of time will be provided.

2. METHODOLOGY

Tests and evaluations for those up to 2016 were carried out according to the Regulation on occupational safety measures (Off. J. SFRJ. 1992, 21) [2] and ISO 9612:1997 [3], and for those after according to the Regulation on preventive measures for health and safety (Off. J. RS. 2011, 96) [4], ISO 9612:2009 [5], ISO 9612:2025 [6], DIN 45645-2 [7], ISO 11690-1 [8], and VDI 2058-3 [9].

The difference is in the assessment procedure and in the limit values. Until 2016, rating was carried out before comparison with both limit values in terms of hearing protection and in terms of interference with work activities,

Table 2 Limit values for assessing the risk of hearing damage

	Regulation [1]	Regulation [2]	
Quantity	Rated level, L_r	Daily noise exposure level, $L_{EX,8h}$	C-peak sound pressure level, $L_{p,Cpeak}$
Limit value	85 dB		
Lower exposure action value		80 dB	135 dB
Upper exposure action value		83 dB	136 dB
Exposure limit value		85 dB	137 dB

Table 3 Limit values for the level range underneath the given risk of hearing damage

	Regulation [1]	Regulation [2]	ISO 11690-1	VDI 2058-3
Task	Rated level, L_r	Rated level, L_r	Rated level, L_r	Rated level, L_r
Working on a money counting machine	70 dB	70 dB	45 – 55 dB	55 – 70 dB
Office work	55 dB	55 dB	45 – 55 dB	less than/equal to 55 dB

2.2. Instrumentation

Measurements were made by using integrating-averaging sound level meters, including the microphone and associated cables, that meet the requirements for IEC 61672-1, class 1 instrumentation.

2.3. Selection of measurement strategies

ISO 9612 Strategy 1 [6] – Task-based measurement was chosen as appropriate. The work performed during the day is analysed and split up into a number of representative tasks, and for each task separate measurements of sound pressure level are taken.

The effective noise exposure time of workers in count rooms of bank cash processing centres is most often between 4 and 6 hours during an eight-hour work shift, while the remaining time is spent on administrative tasks, preparing money, packing shipments, and breaks. Depending on whether they were working in large central, regional or local cash processing centres, workers estimated the time spent working on the machines to be between 4 and 7 hours.

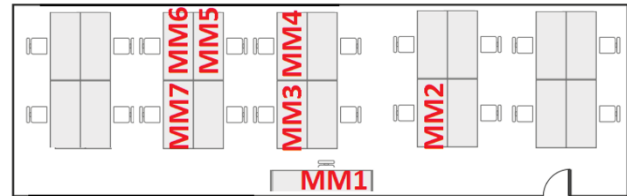
2.4. Work and measurement conditions

The tests were conducted under normal operating conditions, with the machines operating simultaneously as usual.

The design of the workspace itself greatly influences the measured noise levels and exposure of workers at the workplace, starting from the number of workstations and

machines, the dimensions of the room, and the arrangement of workstations and machines.

In almost all large centres, a layout of workstations with counting machines is found, with workstations for working on computers between them, whereby in practice, the work process takes place simultaneously, with one person counting money and the other doing office work. In one newer centre, the office workstation was separated but still exposed to the noise of the money counting machines. An example of the layout of workplaces in one main cash processing centre is given in the sketch in Fig. 1. Here clerical work is performed at the desk marked MM2 while at the others money is counted.

**Fig. 1** Design of a large cash processing centre

3. MEASUREMENT RESULTS

Periodic measurements and tests were carried out in three banks at 27 locations covering large central, regional and local cash processing centres between 2014 and 2026. Table 4 shows data for the main cash processing centre of Bank 1 over the years.

In Table 4, the 'Machine type' column refers to the type of money counting machine. The 'Number of machines in room' row refers to the number of money counting machines. In the row Noise exposure the data refers to the employees' estimate of how much time they spend on tasks and refers to counting money on machines. In the column Machine type the data clerical work refers to the measured noise level at a workplace where money is not counted but where work is done at a computer in the environment of machines that are simultaneously counting money.

It can be seen that Table 4 is missing data for C-weighted peak noise level for measurements before 2016. This is because until then the impulsivity of noise was evaluated by the "impulse"-weighted equivalent continuous sound level L_{pAeq} , and was later replaced by the requirement for the measurement and evaluation of $L_{p,Cpeak}$ (see Table 2).

As for the values given in brackets in the surcharge K_1 column, these are the measured values of L_{pAeq} for the case when the difference $L_{pAeq} - L_{pAeq}$ (see Table 1) exceeds 6 dB.

For Bank 1 cash centres in Locations 1.1 and 1.2 between 2015 and 2020 merged to Location 1.2.

The Table 4 does not show other information that might be needed for a more complete assessment of working conditions, for example the dimensions of the work space, the quality of lighting and the supply of fresh air, both due to a lack of data and to avoid overloading the data with excess information. This will be discussed in the next chapter.

Table 4 Measurement results

Bank	Machine type		$L_{p,A,eqT}$ [dB] (A)	K_1 [dB]	L_r [dB]	$L_{p,Cpeak}$ [dB]
Bank 1, Location 1.1 Main centre						
Year	2015	Noise exposure			7.5 h	
Room 1						
Number of machines in room					4	
	Tellac-9	75.9	3.1	79.0	n/a	
	Tellac-16	72.9	2.3	82.1	n/a	
	ST-350	81.0	2.1	83.1	n/a	
	SB-2000	78.5	3.3	81.8	n/a	
	c. work	74.0	-	74.0	n/a	
Room 2						
Number of machines in room					1	
	SB-2000	78.5	2.4	80.9	n/a	
Location 1.2		Main centre				
Year	2015	Noise exposure			7.5 h	
Number of machines in room					4	
	ST-350	79.7	2.3	82.0	n/a	
	iSniper	78.0	-	78.0	n/a	
	SB-2000	77.4	2.6	80.0	n/a	
	Tellac-16	84.4	3.6	88.0	n/a	
Location 1.2		Main centre				
Year	2020	Noise exposure			7.5 h	
Number of machines in room					6	
	Glory	82.3	-	82.3	102.9	
	c. work	64.7	6 (77.1)	70.7	110.3	
	ST-350	80.1	3.3	83.4	104.9	
	NC7100	77.5	-	77.5	98.0	
	K6	68.9	4.3	73.2	92.8	
	NC-6500	69.0	3.3	72.3	91.8	
	LIDIX	71.2	5.7	76.9	96.7	
Location 1.2		Main centre				
Year	2026	Noise exposure			7.5 h	
Number of machines in room					7	
	c. work	61.5	-	61.5	85.4	
	Glory	82.4	-	82.4	98.2	
	Glory	81.3	-	81.3	106.8	
	c. work	77.2	6 (84.7)	83.2	113.0	
	ST-350	79.9	-	79.9	107.2	
	Hitachi	80.5	-	80.5	104.3	
	Glory	79.9	-	79.9	107.2	
	K-5	80.9	-	80.9	103.3	
	c. work	68.4	6 (74.5)	74.4	96.2	
	ST-350	81.0	6 (91.2)	87.0	117.9	

4. DISCUSSION

4.1. Type of noise

From Table 4 it can be seen that the noise that occurs is often of the impulse type. It is noted that in earlier measurements it is more often characterized as impulsive than in more recent ones. There are two reasons for this, the first is in the surcharge K_1 criterion (see Table 1) which has been changed from 2 dB to 3 dB so that noise that would previously have been defined as impulsive would now not be (if the difference between the impulse-weighted equivalent continuous sound level and the A-weighted equivalent continuous sound level is between 2 and 3 decibels). The second is the emergence of new devices

that count large amounts of money faster (e.g. Glory UW-F16, BPS C5 G+D 25). The counting speed is over 1000 banknotes per minute, which gives an interval between two impacts of less than 0.06 seconds and falls into quasi-impulse noise [12], i.e. the impacts are so close that they are not perceived as impacts. Also, loading a large amount of money means fewer interruptions to load the machine that would be perceived as impulses. In Fig. 2, the graphs show the time-domain waveform of the noise emitted by Lidix and Glory machines.

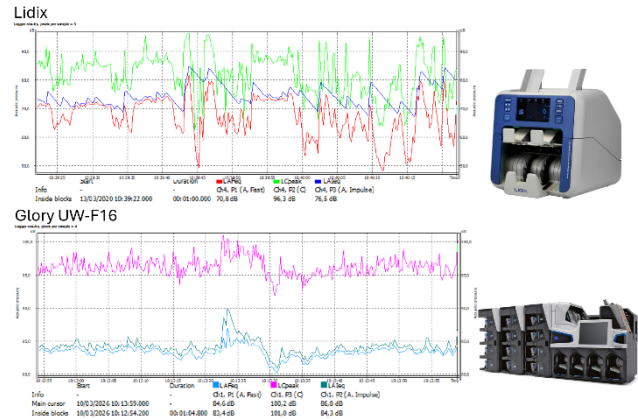


Fig. 2 Time-domain record of noise emitted by money counting machines Lidix ML-2F and Glory UW-F16

4.2. Longitudinal study and noise contribution model

If we look at the average exposure of workers in cash processing centre over time, the noise level has increased. An overview of the results is shown in Fig. 3. Y-error bars in graphs are standard errors of the mean. If we compare the data from the sample for each location separately out of the 5 for which there exist multi-year data, the noise level has increased in 4 and decreased in one. As mentioned in Chapter 3, it is not the same setting, over the years, the space, layout and number of machines have changed. In order to control for the influence of the geometry of the space and the number of devices, we observe only locations that have not changed (occupying the same space all the time) and at the same time we take into account the number of devices that are in use simultaneously. The data is given in Table 5.

In order to compare the noise levels with respect to the number of machines in the space that are used at the same time, we can start from the noise contribution model. In the simplest model, we consider only the number of machines in the room, ignoring the influence of the types of banknotes being counted, geometry of the room and the layout of the machines. Let us assume that, apart from the machine on which the operator works, the noise level at his workplace is influenced the most by the neighbouring machines by one amount, and then by those more distant by one smaller amount. For example, if only the machine on which the operator works were operating and producing a noise level of 79 dB, if the neighbouring machine were located practically right next to it, the contribution of the first neighbour would be equal to the noise from the machine and the noise would be twice as high, which is 3 dB more according to the noise addition rule. Since the

machines are further away, we can assume a smaller contribution from the first neighbour for the model, for example four times smaller, which is a 6 dB smaller contribution. If we now assume that each additional distant machine contributes half as much noise at that location, that is 3 dB less for the contribution. In this simple model, we will assume that the machine has only one first neighbour contributing 73 dB, that each subsequent distant neighbour contributes 70 dB and that the noise contribution from these subsequent neighbours is equal to the contribution of the first distant neighbour. The noise contribution values modelled in this way are given in Table 6. Noise level is the sum of the main term and the contributions from all other machines.

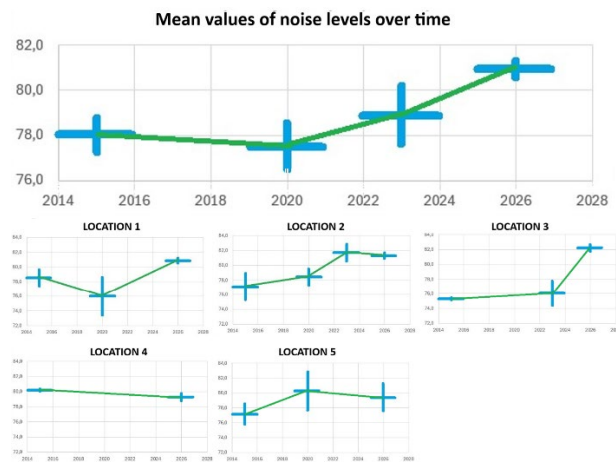


Fig. 3 Average exposure over time for all locations and separately by location

Table 5 Average noise levels at the same locations over time and the number of machines operating simultaneously

Location	Year	No. of machines	Mean noise level [dB]	Standard error of the mean [dB]
1	2015	4	79.9	1.6
	2020	6	76.0	2.6
	2026	7	80.8	0.3
2	2020	4	78.4	1.1
	2023	6	81.7	1.2
	2026	7	81.3	0.3
3	2023	6	76.1	1.7
	2026	4	82.2	0.4
4	2015	2	80.2	-
	2026	2	79.3	0.5

Now we can test the model by calculating the average noise for each situation (number of machines) and correcting the level by the value from Table 6 (addition to main term) to get the value of the main term for each situation, according to the model this is the average noise level of the machine when it is the only one operating in the room. The values are given in Table 7.

Table 6 Noise contribution model (all levels are expressed in dB)

No. of machines	Main term	First amount	Second amount	Third amount	Fourth amount	Fifth amount	Sixth amount	Noise level	Addition to main term
1	79							79.0	0
2	79	73						80.0	1.0
3	79	73	70					80.3	1.3
4	79	73	70	70				80.8	1.8
5	79	73	70	70	70			81.1	2.1
6	79	73	70	70	70	70		81.4	2.4
7	79	73	70	70	70	70	70	81.7	2.7

Table 7 The values given by the model for the main term in the contribution model for each situation of the number of machines

No. of machines	Sample size	Mean noise level [dB]	Standard error of the mean [dB]	Main term [dB]
2	2	79.8	0.5	78.8
4	3	80.2	1.2	78.4
6	3	77.9	1.9	75.8
7	2	81.1	0.3	78.4

From the values for the main term given by the model it can be seen that the model fits in situations with 2, 4 and 7 machines, giving a value for the noise from one machine of 78.5 dB within the standard error (0.3 – 1.2 dB). In the situation with 6 machines the value it gives, 75.8 dB does not seem to be within the deviation limit of 1.9 dB from the value it gives for the other situations. However, if we look at the most extreme outlier, the mean level at location 1 from 2020 of 76 dB (see shaded in Table 5), we see that this value has the largest standard error of the mean, 2.6 dB, of all the data on which the model was tested and that this value is actually within the deviation limits. We see that this model gives an average noise emission level from a single machine of 78.5 dB within a standard error of the mean of 0.7 dB and that it explains the increase in noise exposure levels with the increase in the number of machines in the workplace. Based on this, the trend of increasing noise exposure over the years (Fig. 3) can be attributed to the increased number of machines.

If we want to observe the contribution of a particular type of machine to noise exposure, we can extract measurement data taken at its operator's position from all tests. Table 8 gives data for 4 types of machines most represented in the sample. The average level of operator exposure for a specific type of machine was calculated, as well as the average level calculated when the contribution of other machines in the environment is subtracted according to the noise contribution model. The average level for a machine is the average of the exposure for machines of the same type in all measurements, the noise originating from the machine is the average level obtained from all measurements for a machine of the same type corrected for the number of machines in the room according to the noise contribution model (by subtracting the term Addition to main term from

Table 6). It can be seen that for the Hitachi iHunter iH110 machine, the corrected data are closer to each other than the original data (the standard error of the mean of the corrected values is smaller than the standard error of the mean of the original values), which is in favour of the noise contribution model. For other machines, the standard errors of the mean values match for the original and corrected data. The larger deviation from the mean e.g. for the Kisan machines can be attributed to the type of banknote being counted. For large machines that simultaneously count and sort large quantities of different banknotes, since all banknotes are processed simultaneously, the type of banknote does not affect the noise level.

Table 8 Level to which the operator is exposed for a specific type of machine and emission from the machine (level corrected according to the noise contribution model)

Machine type	Sample size	Mean noise level [dB]	Standard error of the mean [dB]	Mean noise level of corrected levels for the number of machines	Standard error of the mean [dB]
Hitachi ST-350	15	80.4	0.29	78.2	0.31
Hitachi iHunter iH110	8	79.2	0.85	77.1	0.71
Kisan K5-A	9	81.1	0.63	78.8	0.65
Glory UW-F16	7	81.2	0.48	79.0	0.48

Figure 4 provides a graphical representation of the levels measured for a specific type of machine as well as the calculated emissions from a specific type of machine according to the model.

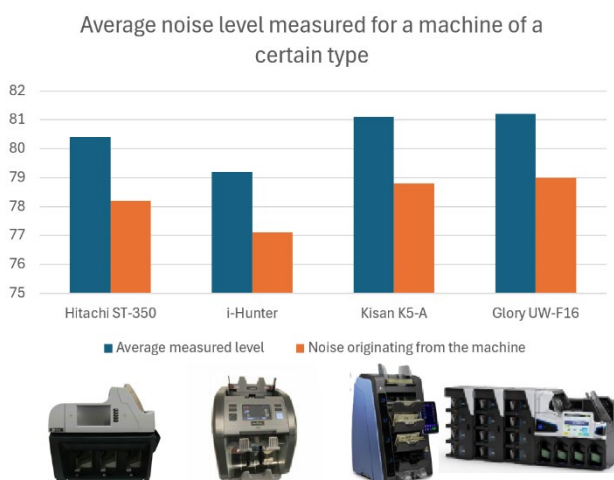


Fig. 4 Average levels measured at the machine of certain type operator's position and emissions from that type of machine calculated according to the model

It can be seen that the levels for smaller machines, Hitachi ST-350 and Hitachi iHunter iH110 are slightly lower (79 – 80 dB measured values, 77 – 78 dB corrected

ones) than for medium, Kisan K5-A and large machines, Glory UW-F16 (81 dB measured values, 79 dB corrected ones).

Based on the discussion, it can be concluded that the trend of increasing noise levels to which workers are exposed can be attributed both to the increase in the number of machines operating simultaneously in the workspace and to the increase in the number of newer, larger machines that have higher noise emissions.

4.3. Comparing to limit values for assessing the risk of hearing damage

In 36 situations in a sample of 67 measurements there is a risk (fields shaded in grey in Table 4) that exposure exceeds the lower action level, and in 6 of these cases there is a risk that the upper action level will be exceeded. Since the exposure is not constant during an eight-hour working day (in central processing centre it is about 7 hours and in smaller centres about 4), when the exposure is recalculated to 7 hours, if we assume that this is the highest expected load, we get that another 6 measurements fall below the lower action level and 4 below the upper one, which leaves 30 situations out of 67 at risk, of which two at risk of exceeding the upper action level.

As for the C-peak sound pressure level, the measured levels are far below the limit values. However, there are conflicting opinions about the peak C-weighted level as an adequate indicator of the harmfulness of impulsive noise, with more recent research suggesting kurtosis and impulsivity as better candidates [11,13].

4.4. Disruptive noise and the synergistic effects

From Table 4 it can be seen that almost all exposure levels when working on money counting machines are around 80 dB which far exceeds the permitted 70, as well as all levels when performing office work in a machine work environment exceed the permissible 55 dB (see Table 3).

Continuous exposure to that noise most often causes chronic fatigue, a drop in concentration that can lead to errors in work, irritability and anxiety, and affects stress that causes transient hypertension and tachycardia. Here, the synergistic effects of working conditions in cash processing centre should also be taken into account. The combination of monotonous work under high responsibility intensifies the negative effects of noise on the psyche [14]. Money dust (money is extremely dirty) and aerosols that occur, for example, in the process of binding money further impair air quality [15], which, in combination with noise stress, can weaken immunity. Additionally, unfavourable physical conditions of the work environment can be burdensome, including cramped space, inadequate lighting and ventilation [16]. As mentioned in the previous chapter, if we analyse additional data on the conditions of these workspaces in which these tests were performed (additional to those given in Table 4), of the 35 cash processing centre locations, 23 have no daylight, 27 have no natural ventilation, 9 of which have only indirect ventilation via adjacent rooms (no direct supply of fresh air to the work area). In 13 cases, the lighting was adequate [17]. An overview of the data is given in Fig. 5.

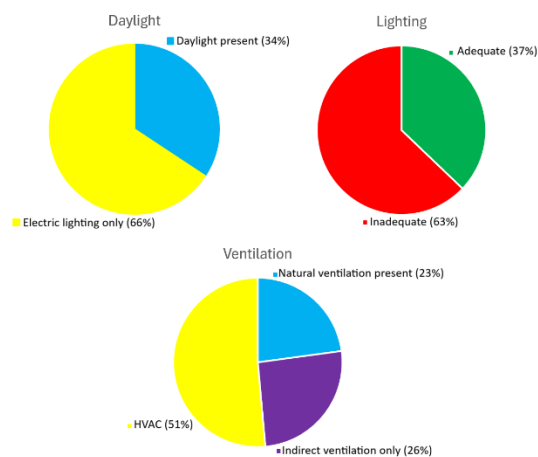


Fig. 5 Working conditions in the cash processing centre in terms of lighting and fresh air supply

Special security procedures within the centres must also be considered; in some banks, opening windows is prohibited, and room doors are required to remain locked. As previously mentioned, these premises are often located in basements and are cramped, accommodating more people and equipment than standard guidelines allow [18]. This is not the case only with new facilities specifically designed for this type of operation.

5. CONCLUSION

Periodic measurements and tests were conducted across 27 locations in cash processing centres of three banks over several years. Depending on the working conditions, varying noise levels were recorded, in nearly all locations significantly exceeded limit levels considered to be burdensome and disruptive at work. Furthermore, synergistic effects – driven by job specificity, physical workplace conditions, and exposure to dust and fumes – heighten stress and can adversely affect overall health. Over time, the transition to newer machinery and the increase in the number of new machines in the workplace have led to a declining trend in the occurrence of impulsive noise and an increase in noise exposure in the workplace. Regarding exposure limits for hearing damage risk, results showed that 30 of the 67 sampled workplaces risked exceeding the lower exposure action value, while two of them risked exceeding the upper exposure action value.

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