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The Importance of Increasing Acoustic and Vibration Comfort in the Passenger Compartment of Road Vehicles Through Soundproofing and Sound Insulation

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Abstract

When designing, specialists must take into account the mechanical, physiological and functional characteristics of users, so that a correlation, a relationship, can be achieved between the dimensional characteristics of the human body and those of car bodies. These are mandatory requirements, implemented with the aim of ensuring and increasing comfort, the feeling of hospitality and the pleasure of driving or being transported in a safe means of transportation. The present scientific research has been carried out by the authors with the aim of highlighting the importance of soundproofing and soundproofing by various methods of the passenger compartment of road vehicles, so that the acoustic and vibrational comfort of the user is one that meets current quality standards. In this way, those interested can get acquainted in the context of the work with theoretical notions about sound, its propagation velocity in fluid materials (gases, liquids) and solid materials, acoustics and acoustic comfort of road vehicle users in the passenger compartment and the purpose, role, methods and materials used for soundproofing and sound insulation of car bodies. In the paper we have also treated a case study based on the active type experiment method (second-order compound factorial experiment method), on the level of noise immission in the passenger compartment of four cars, two with gasoline engine and the other two with diesel engine. Specific conclusions are drawn at the end of the paper.

Keywords: Sound, Noise, Speed of Propagation, Mach Number, Sound Pressure, Vehicle, Passenger Compartment, Acoustic Comfort

1. Introduction

Man lives in a world of sound and noise [1]. Sound is defined by mechanical vibrations in the environment that are transmitted to the auditory system. Noise is powerful, incoordinated sound. On a logarithmic scale, sounds of 10, 20, 30 dB are 10, 100, 1000 times above the lower threshold of sound intensity. Humans perceive sounds with a frequency between 16 and 20,000 vibrations per second and an intensity between 0 and 120 dB (10,000,000,000,000,000,000,743 times above the minimum threshold). The noise produced by a call is between 30 and 60 dB [2]. The level of 20-30 dB is harmless to the human body, this is normal background noise. The sound limit is 80 dB. Sounds of 130 dB cause pain and 150 dB are unbearable [1]. Whether they are audio systems, audible warning systems, horns, gears, gear wheels, tires, engines, gears in transmission systems or chains, rotating and/or translating parts or moving parts, they all contribute more or less in perfect correlation to the smooth, safe and efficient movement of any vehicle on the road. While ensuring the smooth running of the vehicle, they all, in operation, produce sounds, noises and vibrations that are perceived by the user's ear. In order to eliminate the disadvantages of noise, the response of car manufacturers is to design cars and systems or installations which, by their operation, do not disturb users in a disturbing way. This aspect can be achieved by protecting users by fitting, equipping, enveloping the interior of the passenger compartment with a layer that absorbs and reduces the transmission of sounds, noises and vibrations from the source to the interior. Human hearing is a physiological need expressed in a variety of situations: communication, listening to a text, localization of sound sources, detecting the direction of noise sources, etc. The reception and analysis of sounds is a complex process, carried out by means of the only human auditory apparatus (the ears) is a complicated instrument, with the ability to distinguish sounds, noises or vibrations that have varying ranges of frequencies or intensities. This human auditory system allows us to perceive the sounds produced by different sound sources, making the transition from sound to sound sensation. Under the action of sound, signals are transmitted through the transmission system of the human inner ear, exciting the nerve endings of the auditory nerves and transmitting these excitations to the neural pathways of the brain [3]. Under certain conditions, the vibrations imitated by certain sources in the passenger compartment of the car are perceived by the excitatory centers of the human brain as noises. These noises can be: airborne noises (in air or gases), noises in liquids (in the engine cooling system or in the lubricant in the engine oil or in the transmission elements) and noises in solids (noise transmitted in the structure of the vehicle's components (chassis, bodywork, engine, gearbox, main transmission, final drive, wheels, planetary shafts, etc). Road traffic noise is a possible risk factor for medical conditions and incidents. Long-term exposure to noise can produce a variety of health effects, including discomfort, sleep disturbances, adverse effects on the cardiovascular and metabolic systems and cognitive impairment in children. According to findings by the World Health Organization (WHO), noise is the second biggest environmental cause of ill health, after the effect of air pollution (particulate matter). A significant reduction in the number of people exposed to harmful levels of noise is most likely to be achieved not only by applying one-off measures, but also by a combination of different measures, including technological improvements, ambitious noise policies, better urban and infrastructure planning and changes in people's behavior.

2. Literature review and theoretical concepts of sound

Sound is, physiologically speaking, the sensation produced on the perception of the ear of living beings by the vibrations of bodies that are transmitted by sound waves. The human ear is sensitive to air vibrations in the frequency range [20 Hz to 20 kHz], with a maximum of auditory sensitivity around 3,500 Hz [4, pp. 293-297]. This range depends very much on the vibration amplitude, age and health of the receiver. Below the amplitude of 20 μPa vibrations are no longer perceived. With age, the range of sensitivity decreases, especially high frequencies become inaudible [4, pp. 293-297].

Around 1660, the English scientist Robert Boyle proved *that sound waves need a medium through which to propagate* in order to transmit sound over a distance. In other words, *sound does not propagate in a vacuum*. Boyle used a bell placed in a closed, airtight enclosure from which air could be gradually removed. He observed that as the air left the enclosure, the sound made by the bell became fainter and fainter, until it became totally attenuated. Frequency is a fundamental parameter of sound waves and refers to the number of oscillations or complete cycles of a wave that occur per unit time. It is measured in Hertz (Hz). In the context of sound, frequency determines the pitch of the sound. Higher frequencies correspond to sounds with higher pitch, while lower frequencies correspond to sounds with lower pitch. The human audible range extends from about 20 Hz to 20,000 Hz.

Wavelength is the distance between two consecutive points in a wave that is in phase or a complete wave cycle. It is denoted by the symbol λ (lambda) and is usually measured in meters (m). The wavelength of a sound wave is inversely related to its frequency.

Mathematically, the wavelength can be calculated by dividing the speed of sound by the frequency of the wave, using the mathematical relationship:

$$\lambda = v / f \quad (1)$$

where,

λ is the wavelength;

V - sound speed;

F - frequency.

The relationship between these three parameters can be described by the equation:

$$v = f * \lambda \quad (2)$$

where,

V is the speed of sound;

F is the frequency;

λ is the wavelength.

This equation shows that the speed of sound equals the product of frequency and wavelength. In other words, as frequency increases, wavelength decreases and vice versa, while the speed of sound remains constant for a given medium.

Understanding the relationship between sound speed, frequency and wavelength is essential for understanding the behavior of sound waves. Whether analyzing acoustic properties, designing communication systems or exploring the physics of sound, these parameters provide valuable information. By manipulating these quantities, engineers and scientists can optimize various applications, from audio technology to medical diagnostics, ultimately enhancing the understanding and use of sound waves.

From a physical point of view, sound has a broader definition, as it is not related to auditory sensation: any disturbance (mechanical energy) propagated through a material medium in the form of a pressure wave is called sound. This definition also includes vibrations at frequencies outside the sensitivity range of the ear: infrasound (below 20 Hz) and ultrasound (above 20 kHz) [4, pp. 293-297].

From a musical (or esthetical) point of view, sound is an entity characterized by four attributes: pitch, duration, loudness and timbre. Pitch corresponds to frequency (measured in Hertz - Hz). Intensity corresponds to the loudness level (measured in Decibels - dB).

Air molecules tend to move more easily through warm and humid environments because their internal energy increases under these conditions. As the speed of sound depends on how the air pressure varies when the molecules collide with each other (creating areas of compression, but also areas of thinner air), the elasticity of the molecules becomes an important factor. This is why sound travels faster on hot, humid days than on a cold, dry day, when air molecules do not oscillate as easily.

Isaac Newton (b. December 25, 1642 / January 4, 1643, Closterworth, England, United Kingdom - d. March 30/31, 1727, Middlesex, England, United Kingdom) made a major contribution to the understanding of sound propagation through various media, by demonstrating that the speed of sound through certain materials depends on their characteristics. Specifically, the elasticity and density of the propagating medium determine the speed of sound propagation through that medium. Among the factors on which the speed of sound propagation through certain media depends are density and temperature, as well as the state of aggregation of the medium (whether we are dealing with a gas, liquid or solid).

Sound speed is a parameter that describes the propagation of sound through a medium as sound waves. The speed of sound depends on the properties of the propagating medium, in particular its elasticity and density.

In fluids (gases and liquids), only the volume deformation of the medium is involved in sound propagation. In solids, frictional forces are also involved. The general formulas for the speed of sound in fluids and solids are given in Table 1.

Table 1: General formulas for the speed of sound in fluids and solids [5]

The environment	Mathematical formula	Variable
Fluid	$Cfluid = \sqrt{\frac{K}{\rho}}$	▪ $K = -V\frac{\delta P}{\delta V}$, is the volume, adiabatic modulus of elasticity; ▪ ρ – fluid density.
Solid	$Csolid = \sqrt{\frac{E}{\rho}}$	▪ E is Young's modulus (modulus of elasticity of the material); ▪ ρ – solid density.

From a thermodynamic point of view, the speed of sound in gases is given by the mathematical relationship [5]:

$$c = \sqrt{\gamma RMT} \tag{3}$$

where,

γ is the adiabatic transformation coefficient;
R_M - is the constant characterizing the gas;
T - temperature, in ºK.

For the air, $\gamma = 1{,}4$; $R_M = 287$ J/kg.
At normal temperature $T_0 = 273{,}15$ ºK (0 ºC) the speed of sound becomes (ºK), [5]:

$$c = \sqrt{1{,}4 * 287 * 273{,}15} = 331{,}3 \text{ [m/s]} \tag{4}$$

If we consider that the variation with temperature of the adiabatic transformation coefficient is zero, the mathematical relationship (4) for a fluid such as air becomes [5]:

$$Cair = 331{,}3\sqrt{\frac{T}{T0}} = 331{,}3\sqrt{1 + \frac{t}{273{,}15}} \text{ [m/s]} \tag{5}$$

where,

t is the temperature (°C).

Sound waves in solids are composed of compression waves (as in gases and liquids) and another type of sound wave called a shear wave, which only occurs in solids. Shear waves in solids usually travel at different speeds, as shown in seismology.

In fluid dynamics, the speed of sound in a fluid medium (gas or liquid) is used as a relative measure of the speed of an object moving through the medium. The ratio of the speed of an object to the speed of sound in the fluid is called the Mach number of the object. Objects moving at speeds greater than Mach1 are traveling at supersonic speeds.

Mach's number, named after the Austrian physicist Ernst Mach) is a unit of measurement used in aerodynamics and expresses the speed of a body moving in a fluid (projectile, bullet, airplane, rocket, etc). The Mach 1 speed is equal to the speed of sound in the fluid; in standard conditions Mach 1 is equal to 1.224 km/h (or 340 m/s). The Mach number is a dimensionless quantity that shows how many times the speed of a moving thing is greater than the speed of sound in that medium. Subunit values of Mach number mean *subsonic speeds* (slower than the speed of sound), and superunit values mean supersonic speeds. A more detailed classification further defines *transonic speeds* (between Mach 0.8 and Mach 1.2) and hypersonic speeds (greater than Mach 5).

Sound speed in liquids is higher than in gases, because the density is higher (which would mean a higher inertia and therefore a lower velocity), the compressibility of liquids is much lower than that of gases, which makes a pressure disturbance at one point propagate rapidly to neighboring points. Thus, in air the speed of sound is 330-350 m/s, and in water it is about 1500 m/s.

Accurate knowledge of the speed of sound in water is important through a number of areas such as: acoustic mapping of the ocean floor; underwater sonar applications; communications; etc.

The speed of sound in water depends on a number of parameters:

- pressure;
- temperature (approximately 4 m/s at 1 °C);
- salinity (approximately 1 m/s at 1‰).

How this dependence behaves is complex. For this reason, empirical mathematical relationships are used [6]. One such mathematical relationship, simple enough but exact enough, is the one proposed in 1981 by Kenneth V. Mackenzie [7]:

$$c(t,s,z) = a_1 + a_2t + a_3t^2 + a_4t^3 + a_5(s - 35) + a_6z + a_7z^2 + a_8t(s - 35) + a_9tz^3 \tag{6}$$

where,

t is the temperature in degrees Celsius;
s is the salinity in parts per thousand;
z is the depth in meters.

The nine coefficients $a_1, a_2, \ldots, a_9$ are:
$a_1 = 1448{,}96$; $a_2 = 4{,}591$; $a_3 = -5{,}304\times10^{-2}$; $a_4 = 2{,}374\times10^{-4}$; $a_5 = 1{,}340$; $a_6 = 1{,}630\times10^{-2}$; $a_7 = 1{,}675\times10^{-7}$; $a_8 = -1{,}025\times10^{-2}$; $a_9 = -7{,}139\times10^{-13}$

For parameters $t = 25$ °C, $s = 35‰$ și $z = 1{,}000$ m you get the speed value $c = 1550.744$ m/s. The calculation error of the speed within the usual parameter limits is less than 0.2 m/s.

Sound speed in solid materials. In a bar whose cross-section is much smaller than the wavelength of sound, the speed of propagation depends on Young's modulus and how dense the molecules in the solid are, i.e.:

$$Csolid = \sqrt{\frac{E}{\rho}} \qquad (7)$$

For example, in a steel bar the speed of sound is about 5,100 m/s.

When the transverse dimensions of the medium become comparable with the wavelength this formula is no longer correct, the real velocity is higher. For a bar with a cross-section much larger than the wavelength the Young's modulus has to be replaced by the plane wave modulus, *M*, which can be calculated from the Young's modulus and the Poisson's ratio *ν*:

$$M = E\frac{1-\nu}{1-\nu-2\nu^2} \qquad (8)$$

The calculated sound propagation speed is higher. For example, steel has a Poisson's ratio of about 0.3, which results in a sound velocity in a block of steel of about 5,900 m/s.

Researchers at Queen Mary University of London published in October 2021 the results of research carried out in collaboration with the University of Cambridge and the Institute for the Physics of High Pressures in Troitsk, which hypothesized that the theoretical upper limit of the speed of sound is around 36 kilometers per second, about twice the speed of sound in diamond, the hardest natural substance. It is assumed that this maximum speed could be reached in metallic hydrogen (solid atomic hydrogen), which can only exist at pressures exceeding 1 million atmospheres [8].

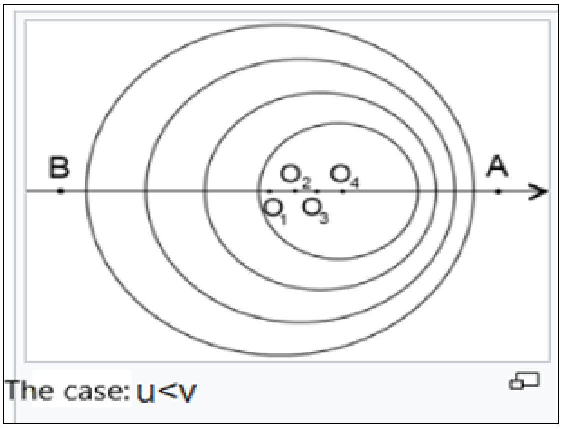

Fig 1: Case: the speed *u* of the sound source is less than the speed of sound *v* [4, pp. 293-297]

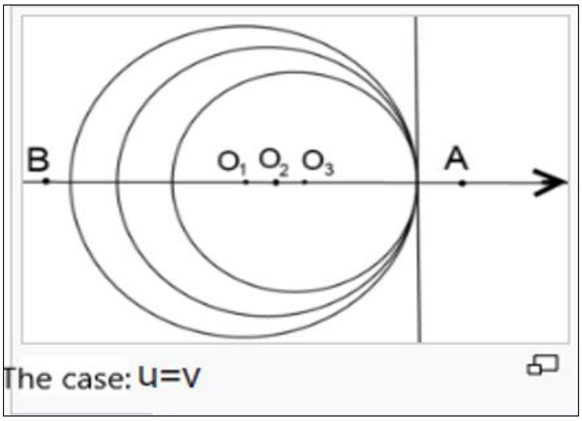

Fig 2: Case: speed *u* of the sound source equals the speed of sound *v* [4, pp. 293-297]

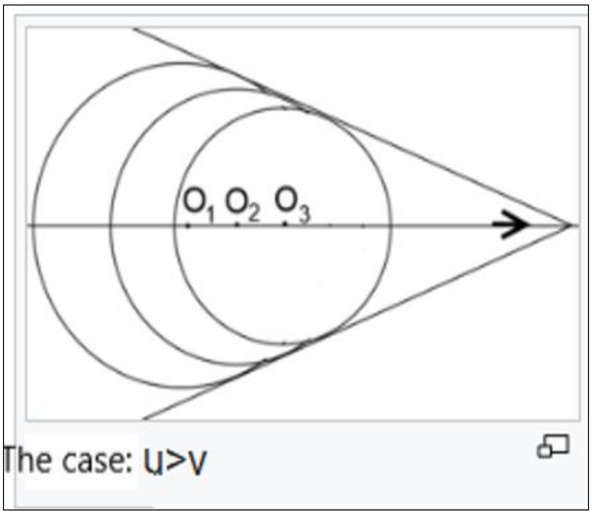

Fig 3: Case: the speed u of the sound source is bigger than the speed of sound *v* [4, pp. 293-297]

When the sound source (assumed to be a point source) is at rest, the sound waves emanating from this point are spherical, the wavefronts being concentric spherical surfaces. If the sound source is moving rectilinearly, the centers of the spherical surfaces will lie on the line representing the source path. Depending on the speed of the source in relation to the speed of sound propagation, we have three situations [4, pp. 293-297]:

- The speed *u* of the sound source is less than the speed of sound *v* (Fig 1). The sound waves are no longer concentric, but agglomerate in the direction of propagation of the sound source. In this case, for an observer A in front of the mobile phone, the sound frequency appears higher (Doppler effect), while the opposite is true for an observer *B* behind the mobile phone;
- The speed *u* of the sound wave is equal to the speed of sound *v* (Fig 2). The spherical waves always have a common point, and an observer in the direction in which the source is moving receives all the sound waves as a pulsed sound (sonic bang);
- The speed *u* of the sound wave is greater than the speed of sound *v*. The spherical waves intersect, and their winding is a cone with its tip in the direction of travel, in front of the source (Fig 3). The angle *φ* between the cone generator and the direction of travel is given by:

$$\sin\varphi\frac{v\Delta t}{u\Delta t} = \frac{v}{u} \qquad (9)$$

An accurate presentation of the speed of sound propagation through different media, structures, or materials is given in Table 2.

Table 2: Speed of sound propagation through different media, structures, or materials [9]

Material	Speed of sound [inch/µs]	Speed of sound [m/s]
Air	0,013	330
Aluminum	0,250	6.300
Bauxite	0,390	9.900
Beriliu	0,510	12.900
Boron carbide	0,430	11.000
Bronze	0,170	4.300
Cadmium	0,110	2.800

Copper	0,180	4.700
Glass	0,210	5.300
Glycerine	0,075	1.900
Gold	0,130	3.200
Ice	0,160	4.000
Chrome-nickel-iron alloy	0,220	5.700
Iron	0,230	5.900
Font	0,180	4.600
Magnesium	0,230	5.800
Mercury	0,057	1.400
Molybdenum	0,250	6.300
Copper-nickel (monel) alloy	0,210	5.400
Chloropen rubber	0,063	1.600
Nickel	0,220	5.600
Nylon 6,6	0,100	2.600
Thermal engine lubricant (SAE W30)	0,067	1.700
Platinum	0,130	3.300
Plexiglas	0,110	1.700
Polyethylene	0,070	1.900
Polystyrene	0,0930	2.400
Polyurethane	0,0700	1.900
Quartz	0,230	5.800
Synthetic butyl, rubber	0.070	1.800
Silver	0,140	3.600
Steel (low carbon)	0,230	5.900
Steel, stainless steel	0,230	5.800
Teflon	0,060	1.400
Staniu	0,130	3.300
Titan	0,240	6.100
Tungsten	0,200	5.200
Uranium	0,130	3.400
Water	0,584	1.480
Zinc	0,170	4.200

If we make a concrete analysis of the data presented in Table 2, we can see significant differences in the speed of sound propagation between different media, structures or materials. The velocity of sound in air (a gaseous fluid) is about 330 m/s, while in steel (a solid material), it reaches 5,800 m/s. Such variations allow us to select appropriate materials for testing during processes or experiments, ensuring accurate and efficient results.
For this reason, it is important to know the speed of propagation of the speed of sound or noise produced by different parts or organs of rotating or translating vehicles. Knowing this propagation velocity, we can choose the appropriate materials for effective soundproofing or soundproofing, which will increase the satisfaction and comfort of road users.
Acoustics comes from the Greek: akuein ακκουειν = to hear. The science of the study of sound.
As a scientific domain it treats with all aspects of sound, such as the production, propagation, influence and analysis of sound.
Acoustics also studies the interaction of sound with materials, propagation in space, as well as the perception of sound and its effects on humans and animals. Acoustics is an interdisciplinary field of research and application, based on different disciplines such as physics, psychology, physiology, information technology, materials science, etc. Sound propagates differently in different environments, which influence the propagation speed and frequency spectrum.
For an elastic wave to cause auditory sensations, it must fulfill three conditions [10]:

- Be have longer than 0.06 s;
- be have an intensity above the audibility threshold 10^{-12} W/m^2;
- be have a frequency between 20 Hz ≤ v ≤ 20 kHz

The area in space where sound waves propagate is called the sound field.
Both longitudinal and transverse waves propagate in elastic medium-solids. In liquids and gases (atmosphere) only longitudinal waves can propagate.
Sound pressure (p) is calculated according to the mathematical relationship [10]:

$$p = \rho c \omega \xi = Z \omega \xi = 2\pi f \xi Z = \frac{aZ}{\omega} = c\sqrt{\rho E} = \sqrt{\frac{P_{ac} Z}{A}} \qquad (10)$$

Sound pressure is measured in N/m^2.
Table 3 shows the International System Symbols and their characteristic physical quantities.

Table 3: International System symbols and characteristic physical quantities [10]

Symbol	International System	Physical size
p	Pascali	Sound pressure
v	Hertz	Frequency
ρ	Kg/m^3	Air density
c	m/s	Sound speed
V	m/s	Particle speed
ω = 2 * π * f	Radians/second	Angular frequency
ξ	Meters	Particle displacement
Z = c * ρ	N*s/m^3	Acoustic impedance
a	m/s^2	Particle acceleration
I	W/m^2	Sound intensity
E	W*s/m^2	Energy density of sound
P_{ac}	Watts	Sound power
A	m^2	Area

3. Interior acoustic comfort in road vehicles

Regardless of the medium (gas or liquid), sound waves or noises take the form of compression waves. Variable overpressure *p(t)*, which is added to the static pressure in gaseous media, is called acoustic pressure. This type of pressure is of particular importance in the field of airborne acoustics or in fluid media.

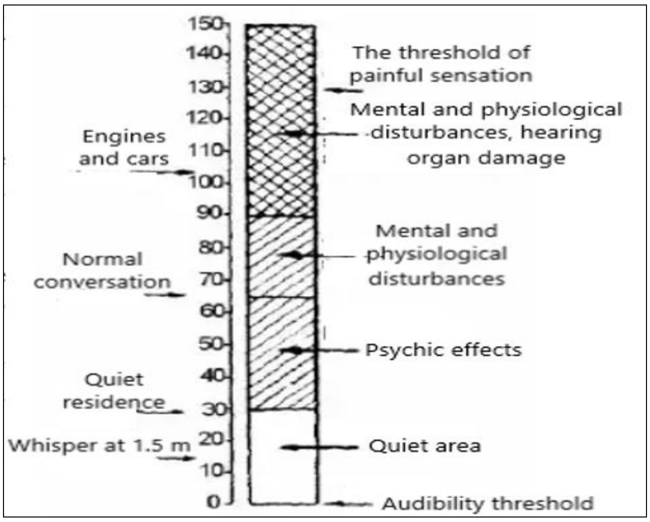

Fig 4: Diagram of the different effects of noise on humans [3, p. 75]

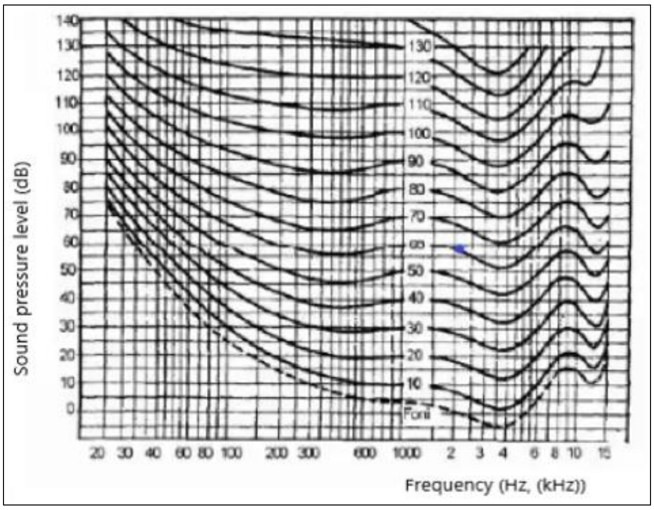

Fig 5: Dependence of sound pressure level on frequency [3, p. 76]

Fig 4 shows the sound pressure levels that correspond to the usual noises perceived by the human ear.

In a defined frequency range for a time interval, the sound pressure takes the form of the effective value $\tilde{p}$.

Thus, the minimum sound pressure that can be perceived by the human ear is $p_A = 2 * 10^{-4}\ \mu bar = 2*10^{-5}\ N/m^2$ (audibility threshold at 1,000 Hz), and the upper limit at the pain threshold, which is $p_D = 2 * 10^2\ \mu bar = 2*10\ N/m^2$ [3].

To make it easier to carry out variable calculations over such a wide range, acousticians have used the logarithmic scale and adopted the decibel (dB) as the unit of measurement.

In this way, the sound pressure level, *Lp*, is defined by the mathematical relationship [3]:

$$Lp = 10lg\frac{p^2}{p_0^2} = 20\lg\frac{p}{p_0}\ [\text{dB}] \tag{11}$$

where,

p_0 is the internationally accepted reference value for the effective (root mean square) sound pressure level;

p – actual measured sound pressure level.

The human ear falls within a dynamic audibility range of 1,000 Hz and is [3]:

$$\Delta L = L_{pD} - L_{pA} = 120\ dB\ [\text{dB}] \tag{12}$$

The human ear's perceptible limit of the difference between two sound pressure levels is 1 dB. The 3 dB difference is quite low perceptible, and clear perceptibility becomes somewhere around 5 dB, with the 6 dB difference representing a doubling of the sound pressure level. At a frequency of 1,000 Hz, the sound pressure level, in dB, is equal to the sound loudness level, expressed in phonos [3, p. 57].

Fig 5 shows the dependence of sound pressure level on frequency. From analyzing the data presented in Fig 5 we see that sound pressure depends on frequency through curves of equal loudness of sound perception by the human ear. The figure also shows a doubling of the loudness value, which is consistent with a variation of 10 phonos.

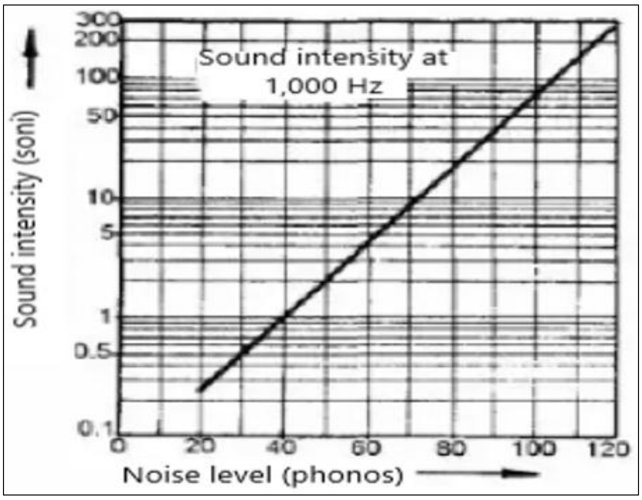

Fig 6: Depends between soni and phonos [3, p. 77]

Sound intensity can also be assessed using another scale, which uses the son as the unit of measurement. This scale is shown in Fig 6. From the analysis of the data presented in Fig 6, it follows that in order to be able to represent these subjective parameters, a proportional scale for subjective intensities has been developed, which is called the sonos scale (in sonos loudness level).

The link between phoni and sonos is given by the mathematical relationship [3]:

$$S = 2^{\left(\frac{P-40}{10}\right)} \tag{13}$$

where,

P is the loudness (phonos loudness level);

S - loudness in sonos (level of loudness in sonos).

Relating the mathematical relation (13) to Fig 6, we see that on the scale a son is defined as the magnitude of loudness at a loudness level of 40 phonos.

The air vibrations perceived by the human ear in the passenger compartment of a car are an accumulation, a combination of several noises that add up to an overall noise. The sources of noise when a car is in use are generated by its mechanical parts (engine, transmission, tires, wheels in contact with the road, relays, current generators, pumps, electric pumps, etc.).

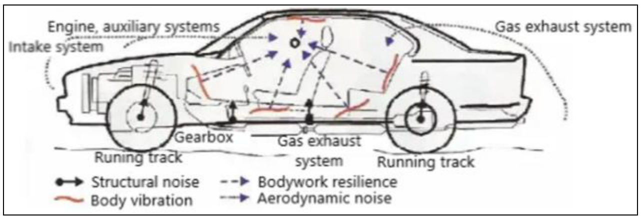

Fig 7: The transfer of noise and vibration to the human ear in the car passenger compartment [3, p. 77]

Noise is transmitted into the passenger compartment both airborne and solidly through body parts. The vibrations perceived in the passenger compartment of the car are imitated by changing the air pressure inside the car and finally reach the user's ear (Fig 7). Analysis of the data presented in Fig 7 shows that any noise or vibration perceived inside or outside the passenger compartment is a vibration of the surrounding air.

The problem of studying and combating motor vehicle noise is a complex, multi-faceted one, covering a number of aspects, including [3, p. 77]:

- study of the physical aspect of noise occurrence, noise source detection and spectrum analysis;
- the study of the quality of the noise level generated by different car components at different load or speed regimes;
- establishing a complex of solutions to combat sources of noise or to prevent its propagation into the environment.

The structural vibrations of the road vehicle body are perceived by the receiver in the passenger compartment exclusively in the low-frequency range. In order to reduce the noise and vibrations in the passenger compartment of the automobile, caused by mechanical elements, parts or organs in rotation or translation, specialists and researchers in the field act both by reducing the dynamic forces occurring during their operation and by reducing the mechanical impedance of the elastic elements of the body. At the same time, the possibility of increasing the mechanical impedance of the source and the body at the points of attachment to the elastic connecting supports is also being pursued.

In the high-frequency domain, noise reduction is achieved by calming the vibrations of the panels that limit the body. The main lines of action target the three fundamental parameters of an elementary system: mass, stiffness, damping [3, p. 59].

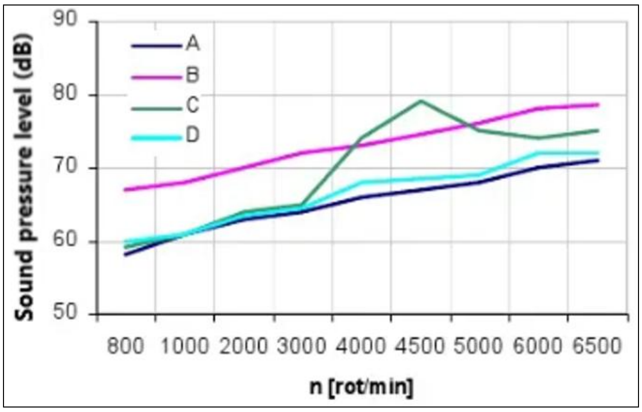

Fig 8: The main acoustic deficiencies of cars.
A - satisfactory car; B - average sound level too high; C - resonance; D - medium and high frequencies too high [3, p. 78]

Fig 8 shows the main acoustic deficiencies of road vehicles. From the analysis of the data presented in Fig 8, it can be seen that in qualitative terms, compared to a satisfactory vehicle - curve A, both in terms of sound level and sound pressure, the vehicles show three categories of deficiencies [3, p. 79]:

- the sound level is mainly due to the low-frequency components, which may be too high over the whole range of normal operating modes or over a large part of it (curve B);
- the overall level may pass through a maximum point (resonance) at a given engine speed or travel speed (C curve);
- mid- and high-frequency components may exhibit too high an acoustic pressure level, which reduces the intelligibility in the passenger compartment.

Four characteristic weighting curves are internationally recognized, type A, B, C and D (Fig 9). The most widely used is the A-type curve for common sound pressure levels and the D-type curve for aviation noise measurements.

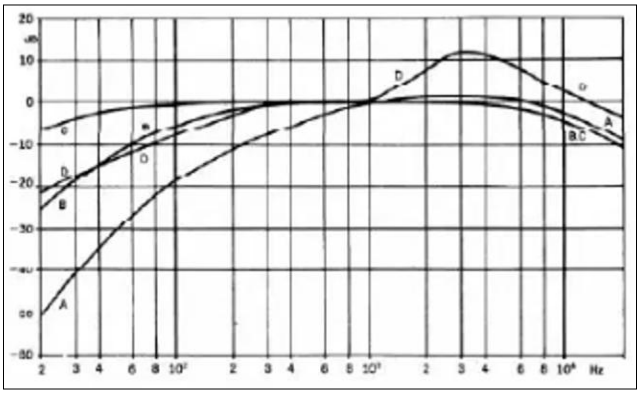

Fig 9: Weighting curves used in the construction of acoustic measurement equipment [3, p. 79]

Today, manufacturers of road vehicles carry out vibration comfort studies at the design stage by analyzing computer-simulated vibrations using the finished product. In this case, the prototype vehicle is placed in an anechoic chamber. An anechoic chamber is an enclosure, a well-soundproofed container with 1.2m-thick walls, where prototypes are "encased" in sound-absorbing materials to prevent reflected noise. Here there is a roller stand that perfectly mimics real-life driving conditions, up to speeds of 200 km/h, and a system that ventilates the air inside the 33,000 m^3 chamber. These two systems work in tandem with an air cooler to ensure the optimum temperature for testing. The test results determine that the influence of the engine air intake and exhaust systems on overall noise is reduced.

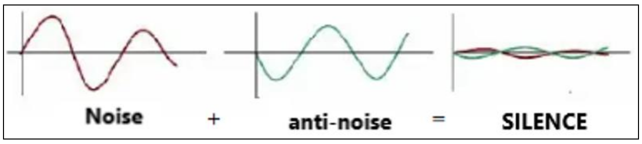

Fig 10: Active noise control [3, p. 80]

To improve acoustic comfort, more and more road vehicles (especially passenger cars) are using Active Noise Control (ANC) technology. ANC technology is based on the principles of "destructive interference", which involves generating a vibration that is 180º out of phase, but of the same frequency and amplitude as the interfering waves (Fig 10). In other words, the unwanted noise is eliminated by an identical vibration through the ANC module, which processes the data and emits mirrored vibrations through the speakers of a cassette player [3, p. 79].

Vibroacoustic simulation has become an immanent part of the car design process. In this sense, the NVH (Noise, Vibration, Harshness) process is a complex process composed of a multitude of factors and imposed requirements. The process takes into account the subjective opinions imposed by customers and analytical calculations obtained by CAE (Computer Aided Engineering) modeling.

Bruel & Kjær's vision in the automotive sector is to secure customer requirements with components and systems for both manufacturers and suppliers. On the other hand, the company has expanded the acoustic engineering portfolio by supplying devices for the NVH process, which can be used for all stages of automotive programs, from assortment definition to project details. Developing a process where all available acoustic and vibration data can be understandable, that can also communicate with other factors in the vehicle program will ensure that the right decisions are made as easily as possible to save time and effort [3, p. 80].

Determination of the sound pressure level at the ear of the road vehicle user is the quickest way to determine acoustic comfort.

Considering the first and last elements of the structural noise pathway, we define [3, p. 81]:

- point mobilities v_i/F_i, defined as the point speeds i, per unit external force on that point;
- equivalent radiant power, given by the mathematical relationship [3]:

$$Pi(\omega) = \frac{1}{2}\,\rho\, c \int_{Ai} |v(\omega)|^2\, dA \tag{14}$$

where,

Ai is the surface area;

v – he actual measured speed value;

ρ – density;

c – speed of sound in air.

The mobilities can be calculated very efficiently and provide a sufficient measurement for the local energy input to the body. Unfortunately the mobilities and the pressure level in the passenger compartment are not always correlated and for this reason the action of several sources presents a problem in terms of their contributory addition. When the coherent sources are added, the resulting effective sound pressure level is the square root of the sum of the squares of the individual sound pressure levels.

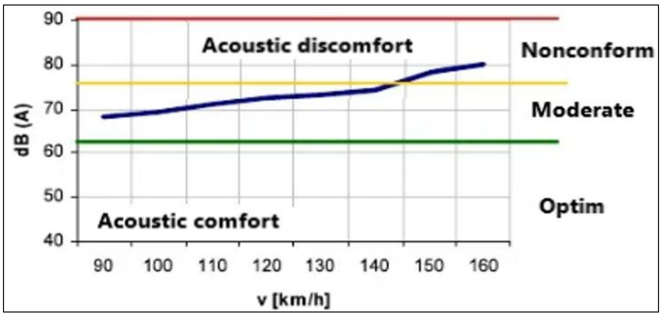

Fig 11: Acoustic comfort assessment [3, p. 80]

In Fig 11 we present an assessment of the acoustic comfort in the passenger compartment of a passenger car, by the sound pressure level in relation to the traveling speed.

Analysis of the data presented in Fig 11 shows that moderate acoustic comfort is achieved at speeds in the range [90 - 148 km/h] and passenger compartment noise in the range [68 - 76 dB(A)]. Acoustic discomfort occurs after the car reaches a speed higher than 148 km/h and a noise level higher than 76 dB(A).

4. Vehicle body soundproofing and sound insulation. Purpose, role, methods and materials used

The qualities you expect from a car should invariably include fuel efficiency, an appropriate level of safety and good reliability.

One of the most important aspects of car comfort, as well as passenger safety, is soundproofing the interior. This involves placing materials with special properties that isolate sound and vibration.

Soundproofing s to block the passage of sound from the passenger compartment to the outside and vice versa. This is done with low-density materials such as sponges, felt, etc.

Sound insulation is vibration control and is achieved with bituminous materials that convert vibration into low-intensity heat. When applied to certain machine components (sheet metal, plastics, e.g. door panels, dashboard, etc.), the mass of the assembly is increased and with it the inertia and rigidity of the movement, also modifying the resonant frequency of the part in question. This eliminates noise and/or rattling and at the same time considerably improves the dynamics of the road vehicle's audio system, as well as comfort

Unfortunately, many modern cars do not have very well-designed soundproofing, unlike luxury brands, where this is treated with the utmost care. For the driver, soundproofing for certain driving frequencies is extremely important to isolate the noise produced by the engine, especially for diesel engines which are a major generator of noise and vibration.

Resonance is a particularly important phenomenon that occurs when two car components operate at the same frequencies. When this phenomenon occurs, such as when the engine is under-loaded, certain components vibrate, producing noise and vibrations that are annoying for the driver and passengers.

Fig 12: First vibro-absorbent layer [11]

Fig 14: Third sound absorbing layer [11]

Fig 15: Engine bonnet sound isolation [11]

The sound insulation materials have been specially designed to reduce noise caused by vibration. Each material has been carefully designed to fulfill an important role in the sound insulation process.

There are three types of sound insulation: vibro-absorbing, thermo-absorbing and phono-absorbing. Each has a specific role, as follows:

- ***vibro absorbent**:* a material made of butyl rubber and aluminum foil, which completely absorbs vibrations. It is applied as a first coat to all sheet metal surfaces of the machine (Fig 12).
- ***thermo absorbent***: a material that acts as a thermal barrier but also acts as a sound insulator, as this type of material is made of polyurethane foam, which is designed to block sound waves. It is applied as a second layer, directly over the vibro-absorbent (Fig 13).
- ***phono absorbent***: is the last layer, made of open-cell polyurethane foam, which absorbs the last frequencies that have passed the first two layers. We recommend this material especially on plastic door panels, because the sound is absorbed, not blocked, so it creates a pleasant acoustic in the car (Fig 14).

There are two types of polyurethane foam:

- ***closed-cell foam***, which is ideal for damping low-noise noise from road, engine, etc;
- ***open-cell foam***, which absorbs mid and high frequency sounds.

Fig 15 shows how to soundproof the engine bonnet. Sound insulation of the engine bonnet and engine compartment is done in order to reduce the level of sound and/or noise emitted externally by the engine. A large part of these sounds and noises are transmitted into the passenger compartment from the engine through the floor and wall separating the engine compartment from the passenger compartment, but a large part of the sounds and noises are transmitted through the air outside the car via: *the bonnet - outside the car - windshield - windows - vehicle door - rear window - inside the passenger compartment - human ear perception.*

Fig 16: Sound insulation of car doors [14]

Sound insulation can be achieved by applying a sound insulating layer of sound absorbing material (sponge or felt) to the inside of the engine bonnet. The same type of material can also be used to insulate the bonnet or boot lid. Fig 16 shows how to soundproof car doors. Also, to reduce the penetration of sound or noise into the passenger compartment, both the windshield and the rear window of the bodywork and the door windows should be made of materials (glass) with absorbing properties, with a reflective function, which propagate sound waves and reflect them outwards.

The need for a quieter interior is particularly evident in budget car models. Many car manufacturers choose to cut costs where it's not so obvious, and the lack of perfect soundproofing is not considered as big a shortcoming as the lack of comfort features such as automatic air conditioning or rain-sensing wipers. However, a car in heavy use can become a source of discomfort, especially if many kilometers are driven in a short unit of time. This happens due to a combination of two distinct processes

On the one hand, there is the noise produced when touching the road surface, which will be louder the rougher and more irregular the texture of the asphalt. On the other hand, the resonance produced by the frequencies emitted by certain components, driven by the vibrations of the engine, is also felt to the full, especially in older vehicles. In order to prevent these vibrations from becoming as annoying as they could be, many car owners choose to damp them with materials applied to the fenders, doors, boot and dashboard

Car wings are like amplifier boxes for certain frequencies, especially if not properly soundproofed. To soundproof fenders, a coat of primer is applied to the inner surface of the fender, followed by two to three coats of sound deadening paint (a rubberized paint). In this way, by adding sound-absorbing and vibration-damping materials, sound will no longer be transmitted into the passenger compartment as it was before soundproofing.

In the doors and trunk, layers of sound-absorbing materials can be applied with aluminum foil on the inside. These have a special adhesive that adheres to the door surface.
There are also more professional solutions, which involve using a hot air blower to apply the foil to the inside of the bodywork. A less expensive, though not desirable, solution is to place very inexpensive materials, such as air-filled plastic sheeting similar to packaging. If you do this yourself, it's best not to apply moisture-retaining materials to the doors.
Under the body of the car, you can also apply anti-tarnish paint, but avoid areas that are close to the car's exhaust system, as this area gets very hot. A more difficult operation is to insulate the metal surfaces in the dashboard. To do this, you will need to remove the dashboard and apply felt and aluminum foil to the metal surfaces. It is advisable to leave this procedure to the professionals, especially if you have never done it before.
There are very expensive sound insulation materials available, but they have special properties. Depending on the car, more than one soundproofing material may need to be applied to isolate more frequencies. For better soundproofing, cheders can be added to certain areas of the car, such as the doors or the bonnet, if the car model allows it. There are also dampers that can be glued to the metal surface of the car.
In order to evaluate the sound insulation operation, we observe how the car behaves with the engine idling, at city driving speed and at speeds over 100 km/h. At idling speed it is necessary to listen to how much the engine can still be heard, and at speeds above 100 km/h the wind noise produced by the wind in contact with the car is assessed.
You can also inspect how the sound insulation has been made and by closing the doors to listen to the sound they make. An inexpensive commercially available sound level meter can also be used to accurately measure the decibels produced before and after soundproofing. In this case, the noise level will be measured at different points in the car interior, the most important being the area near the driver's head and the area near the rear passengers.
Here, then, are the operations and the materials required for these operations, which are used to make the soundproofing:

- apply a primer and a minimum of two coats of anti-fade paint to the inside of the wings. Wait a few minutes between coats and keep the metal surface free of rust spots or greasy areas;
- the introduction of low-density sound-absorbing materials, such as sponge or felt, on the inside of doors and tailgate or trunk lid. The thickness of these materials varies between 1.8 and 2.5 mm and can be found in packets, in sheets;
- cleaning, degreasing and painting of the chassis with a special synthetic rubber-based paint with an anti-knocking effect. It shall not be applied in the vicinity of exhaust system components;
- dismantling the dashboard in order to fit pieces of felt or aluminum foil to reduce the resonance that can be transmitted from the engine to the passenger compartment.

The following materials can be used to reduce vibrations in key areas (door area, floor, engine compartment): STP Diamond Aero; STP Black Gold; STP Black Silver; STP Beat On; STP GB 2 [11].
For sound insulation of car bodywork of the thermo/phone type it is recommended to use the following materials: STP Aero Flex 6/10 mm; STP Biplast 5/10/15 mm; STP Acceent 6/10 mm [11].
Other material combinations used: STP Diamond Aero, Aero Flex 6, STP Biplast 15 Wave; STP Black Gold, Accent 6, Biplast 15 Wave; STP GB 2, STP Splen 04, Biplast 10 [11].

5. Analysis of imitated sounds in car compartments. Case study

In order to be able to make a concrete analysis of the sounds and noises imitated in the passenger compartment of passenger cars, we propose to carry out a research in this field on four passenger cars, two with spark ignition engines and two with compression ignition (Diesel) engines.

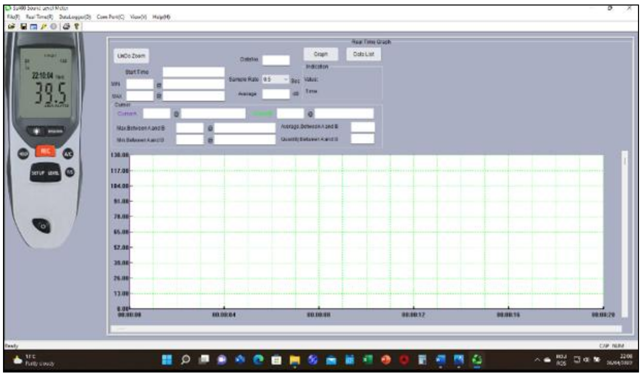

Fig 17: The software interface of the SL-400 Professional Sound Level Meter

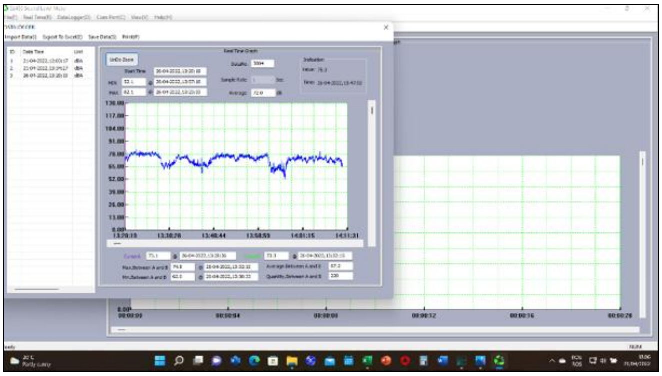

Fig 18: Line graphs made with the SL - 400 Sound Level Meter

The sounds and noises emitted by the different sources in a car are received by the human ear in the passenger compartment as ***imitated sounds***. For this reason we will talk about ***imitated sounds***, ***imitated noises.***
The experiment used in this research is ***the active type experiment method (second-order compound factorial experiment method).***

- **To get concrete data**, in the experimental research we used cars with different physical and moral uses, with different classes of soundproofing/soundproofing that determine the comfort of the users, but also different European pollution standards.

A sound level meter type SL - 400 was used to measure the sounds and noises imitated in the passenger compartment of the cars.

The SL 400 professional sound level meter is a device that meets the requirements for noise measuring instruments, accuracy class 2 according to IEC 61672-1 as well as ANSI S1.4 and is recommended for documenting road traffic noise, workplace measurements or environmental auditing. The four-position display has bar graphical representation, which can be easily read in any condition, even in the dark, thanks to the backlit LCD display.

The device performs sound frequency evaluation according to A and C characteristics, a Fast-Slow time evaluation and has many other practical functions.

The SL-400 Professional Sound Level Meter is a perfect solution for professional noise level measurements. The practical format, low weight and one-hand operation due to the optimized key layout make this device the perfect equipment for sound level measurement in workshops and industrial halls, work and environmental protection. The SL-400 professional sound level meter has an additional live logging function and a data memory for up to 32,700 values. The measured values can be simply transmitted via a USB cable to a PC for analyzing the stored data by means of a software included in the package. Fig 1 shows the SL- 400 Sound Level Meter software interface. Also, by means of the software it is possible to realize linear graphs as in Fig 2. For logging and long time measurements, the SL-400 Professional Sound Level Meter can be mounted on a mini-stand included in the scope of supply. The 3.5 mm jack of the instrument offers the possibility of connection to a frequency analyzer or X-Y chart-recorder. Also, via the software it is possible to analyze the data returned by the device. These include: the maximum and minimum value of the recorded sound; the arithmetic mean of all recorded values; the analysis of the data on intervals (between two points marked by the user on the chart).

Fig 19: Professional Sound Level Meter, SL - 400

Fig 19 shows the SL - 400 Sound Level Meter with its accessories.

Practical benefits and technical data, according to the supplier, are as follows:

1. **Practical advantages:** Accuracy class 2 according to IEC 61672; frequency analysis along A and C lines; maximum and minimum display; memory for up to 32,700 values; time evaluation (fast/slow); illuminated display; bar display, graphic; 1/4-inch thread for stand; datenlogger function; analysis software; USB connector and ø 3.5-mm plug; including calibration certificate.
2. **Technical data:** measuring range: 30-130 dB; accuracy:± 1.4; IEC 61672-1 class 2, ANSI S1.4 Typ 2; resolution: 0.1 dB; frequency range: 31.5 Hz - 8 kHz; dynamic range: 50 Db; partial measuring ranges (low): 30...80 dB; partial measuring ranges (medium): 50.... 100 dB; partial measuring ranges (high): 80...130 dB; partial measuring ranges (auto): 30...130 dB; response time: 500 ms; time rating: Slow (S) 1 s, Fast (F) 125 ms; microphone: condenser microphone; power supply: 9-V IEC 6LR61/6P22; operating time without battery change: > 30 h; operating conditions: 0 to 40 °C, 10 to 90% relative humidity; dimensions (L x W x H): 255 x 63 x 45 mm; weight: 305 g; manufacturer: Trotec Germany.

For a more complete analysis, three routes were used for experimental research, two urban routes that were parked with speeds of 30 km/h and 50 km/h respectively and one extra-urban route, a highway, where the maximum speed allowed by the road traffic regulations in Romania, 130 km/h, was used.

- **European maximum permissible limit values for noise emitted by road vehicles in traffic**

The European Union has regularly amended its legislation in an attempt to reduce noise pollution. The first piece of legislation governing pollution standards for motor vehicles is Directive 70/157/EEC/February 6, 1970, which regulated for the first time noise emission limits for motor vehicles and set out technical specifications for measurable levels of noise emitted outside by road vehicles during operation. The Directive was amended by UN-ECE Regulation No 51. Finally, on December 9, 2011, the European Commission is proposing to the European Parliament and the Council a Regulation laying down the noise limit value for noise emitted by road vehicles, repealing Directive 70/157/EEC/ February 6, 1970 [12].

In Table 4 we present the legal sound level limit values as specified in Annex III of the Motor Vehicle Sound Level Regulation issued by the European Commission on April 16, 2014.

Table 4: The legal limit values of the measured noise level as specified in Annex III of the Motor Vehicle Noise Regulation [12]

Vehicle category	Vehicle category description	Limit values expressed in dB(A) [decibels (A)]		
		Stage 1, applicable to new vehicle types from July 1, 2016	**Stage 2, applicable for new vehicle types from July 1, 2020 and for first registration from July 1, 2022**	**Stage 3, applicable for new types of vehicles from July 01, 2024 and for first registration from July 01, 2026**
Passenger transport vehicles of category M				
M_1	Power to mass ratio ≤ 120 kW/1,000 kg	72(*)	70(*)	68(*)

(*) M1 category vehicles derived from N1 category: vehicles with a mass of 2,500 kg must comply with the N1 category limit values (2,500 kg < M1 category mass with R-point > 850 mm from the ground and a total authorized mass ≤ 3,500 kg) [12].

For M1 vehicles, the higher limit values for off-road vehicles are only valid if the maximum permissible mass is > 2 tons [12]. The yellow colored column in Table 4 is the subject of the research. The noise produced by the cars used in the experimental research falls within the sound value of

72 dBA.

Power to Mass Ratio (PMR)

In order to fit each car on which I carried out experimental research into the legal noise standard according to Annex III of the Motor Vehicle Sound Level Regulation issued by the European Commission on April 16, 2014 (Table 4), it was necessary to calculate the power to mass ratio (PMR).

The power to mass ratio (RPM) is determined by the mathematical relationship [12, p. 131]:

$$RPM = (P_n/m_t) \times 1,000 \text{ [kW/kg]} \quad (15)$$

where,

P_n is the rated power and is measured in kilowatts (kW);

m_t - the total mass of the vehicle and measured in kilograms (kg),

but,

$$m_t = m_{ro} \text{ [kg]} \quad (16)$$

where,

m_{ro} is the mass of the vehicle in running order [13, p. 70].

Vehicle mass in running order (m_{ro}) is defined by the weight of an unladen vehicle, with the bucket, freight container or passenger compartment/passenger compartment, with coupling or towing hitch in the case of a towing vehicle, with the weight of the rigid frame (chassis) and driver's compartment (cab), if the vehicle is delivered without bucket or bodywork and/or towing device by the manufacturer, including the full weight of the cooling system, engine and transmission oiling, with the full weight of the fuel tank (90%) and other special fluids (100%). Exception: sewage, dashboard and other instruments, spare wheel, driver with a maximum weight of 75 kg, and for public means of transport (minibuses, trolleybuses, buses, coaches) the weight of the accompanying person is taken into account, which must be max. 75 kg (if the vehicle is equipped with a passenger seat) [13, p. 70].

The power to mass ratio (RPM) is dimensionless.

In Table 5 we present the power to mass ratio (PMR), calculated on the basis of the mathematical relationship (15), for the cars for which the noise emissions were determined.

Table 5: Calculated power to mass ratio (PMR) for vehicles for which noise has been determined

Type	Vehicle make, engine capacity and European pollution standard	Year of manufacture	Engine power [kW]	Vehicle's own mass [kg]	PMR [kw/1,000 kg]
A. Vehicles with spark-ignition engines					
Car	Volkswagen Jetta TSI 1,4 L, Euro 6	2015	92	1.341	**69**
Car	Dacia Solenza 1,4 MPI, Euro 3	2004	55	980	**56**
B. Vehicles with compression-ignition (Diesel) engines					
Car	Renault CAPTUR 1,5 dCi, Euro 5	2020	85	1.387	**62**
Car	Renault Symbol 1,5 dCI, Euro 3	2005	60	1.005	**60**

Immediate conclusion: Analysis of the data presented in Table 5 shows that all passenger cars subject to the noise research fall into the M1 category of passenger vehicles with a power to mass ratio ≤ 120 kW/1000 kg (Table 4). They fall into Stage I which is applicable to new vehicles manufactured from July 1, 2016 onwards, i.e. at the sound value to which the research relates – ***72 dBA***.

Working hypotheses on which the research was based

I.1 At low speeds (30 km/h), car engines run at higher RPM and noise pollution increases. The low-speed (e.g. 30 km/h) flow of vehicles in urban areas leads drivers to use lower gears (max. 2nd gear), both to ensure the necessary power reserve for the car and to avoid using engine speeds below the lower limit necessary to ensure the power supply (under-gearing). This would lead to a higher level of chemical and noise pollution in road traffic compared to 50 km/h, where the power reserve of a combustion engine can also be ensured in the higher gears. That is why it is important to check in practice whether, at low speeds of 30 km/h, car engines run at higher revs and, as a result, the level of noise pollution increases. Following research I will carry out on different types of cars with spark-ignition and compression-ignition (Diesel) engines in an urban environment at 30 km/h, I will demonstrate whether this hypothesis is true or false.

I.2 When driving on a highway, the combustion engine operating at higher engine speed, tire-road contact and friction of the car with the air increase the level of noise. It has been demonstrated in practice that driving any motor vehicle on the highway at the legal speed of 130 km/h or above, with the gearbox in the last gear (economy gear), the engine is running at high revs and the level of chemical and noise pollution increases. That is why we believe that the level of chemical and noise emissions in highway driving far exceeds the level of emissions in urban driving. Following the research that I will carry out on different types of cars with spark ignition and compression ignition (Diesel) engines, in extra-urban environment on the A1-Sibiu highway at a speed of 130 km/h, I will demonstrate whether this hypothesis is true or false.

Specific conditions for conducting experimental research

The conditions under which we carried out the determinations to obtain experimental data on the level of noise pollution measured inside the passenger compartment of motor vehicles, they were carried out in order to define the acoustic comfort provided to the driver and passengers during the vehicle's travel. They were carried out by measuring and recording the sound waves and vibrations produced by motor vehicles when driving in urban environments at different speeds (30 km/h and 50 km/h) and on the highway at the maximum legal speed limit (130 km/h), using a professional SL 400 sound level meter. All data were recorded in the internal memory of the sound level meter.

The data obtained from the experimental investigations are related to the legislative provisions presented in Tables 4 and were transferred to a computer system, through which we processed the experimental data using Excel software.

Also, the processing of the noise data was carried out using the SL-400 sound level meter's own software.
Following the processing of the chemical and noise data, the results were analyzed and interpreted, and based on them the conclusions, further research directions and the databases for the mathematical model of the research were established.
During the experimental research the following conditions were met:
the test was carried out on routes composed of streets of all categories within Sibiu and on the A1 highway, on distances between 5-30 km;

- the accelerations and decelerations were not programmed, but were those required by road traffic rules, the principles of preventive driving and eco-driving;
- speed limits on urban streets: 30 km/h and 50 km/h respectively, and on the highway 130 km/h (in compliance with road traffic rules);
- the cars were equipped with an SL 400 sound level meter for measuring noise emissions, mounted inside the passenger compartment;
- test time was between 15-45 minutes;
- the outside ambient temperature was between +20 and +25 °C;
- all auxiliary equipment that was switched on during the tests (air conditioning, headlights, navigation system) was taken into account;
- the experimental route, both urban and non-urban, was the same for all vehicles.

Fig 20 shows aspects of the experimental research.

Fig 20: Aspects during experimental research

Physical usury and tear of the cars used for the experimental research

It is defined by the number of kilometers driven, and moral wear is defined by age in years. The average of actual kilometers driven per year of age for the other cars with MAS engines used in the experiments is as follows: Volkswagen Jetta 1.4 TSI, Euro 6 - 11,317 km; Dacia Solenza 1.4 MPI, Euro 3 – 9,509 km; The average of the actual kilometers driven per year of age for the cars with MAC used in the experiments is as follows: Renault Captur 1.5 dCI, Euro 5 - 17,480 km; Renault Symbol 1.5 dCI, Euro 3 - 14,053 km.

We specify this because the physical wear and tear of a vehicle can cause a different level of noise pollution (a vehicle whose engine is in an advanced state of physical wear and tear usually produces a higher level of vibration and noise than a newer one).

Results obtained

Centralization of the results obtained by measurements of the sounds and noises imitated by cars in the passenger compartment with dedicated equipment is presented in Tables 6, 7, 8, 9, 10 and 11.

Table 6: Centralizer with the minimum, medium and maximum values of noise measured in the passenger compartment of cars with spark ignition engines, when driving in urban traffic at a speed of 30 km/h

Type and make of vehicle	European pollution standard	Cylinder capacity (cm^3)	On-board kilometers (real km)	Age (years)	Sound values measured inside the passenger compartment dB(A)		
					Minimum	Medium	Maximum
Autoturism VOLKSWAGEN JETTA TSI, car	Euro 6	1.400	113,167	10	56,10	61,50	77,70
Autoturism DACIA SOLENZA, car	Euro 3	1.400	199,688	21	59,20	68,1	83,3

Table 7: Centralizer with the minimum, medium and maximum values of noise measured in the passenger compartment of cars with spark ignition engines, when driving in urban traffic at a speed of 50 km/h

Type and make of vehicle	European pollution standard	Cylinder capacity (cm^3)	On-board kilometers (real km)	Age (years)	Sound values measured inside the passenger compartment dB(A)		
					Minimum	Medium	Maximum
Autoturism VOLKSWAGEN JETTA TSI, car	Euro 6	1.400	113,167	10	55,20	63,00	75,30
Autoturism DACIA SOLENZA, car	Euro 3	1.400	199,688	21	55,80	70,60	85,60

Table 8: Centralizer with the minimum, medium and maximum values of noise levels measured in the passenger compartment of cars with spark ignition engines, while driving on the A1 - Sibiu highway

Type and make of vehicle	European pollution standard	Cylinder capacity (cm^3)	On-board kilometers (real km)	Age (years)	Sound values measured inside the passenger compartment dB(A)		
					Minimum	Medium	Maximum
Autoturism VOLKSWAGEN JETTA TSI, car	Euro 6	1.400	113,167	10	67,10	73,20	89,30
Autoturism DACIA SOLENZA, car	Euro 3	1.400	199,688	21	76,30	81,10	85,50

Table 9: Centralizer with the minimum, medium and maximum values of noise levels measured in the passenger compartment of passenger cars with compression ignition (Diesel) engines, when driving through an urban area at a speed of 30 km/h

Type and make of vehicle	European pollution standard	Cylinder capacity (cm^3)	On-board kilometers (real km)	Age (years)	Sound values measured inside the passenger compartment dB(A)		
					Minium	Medium	Maxium
Autoturism RENAULT CAPTUR 1,5 dCI, car	Euro 5	1.500	87,400	5	51,00	59,2	71,30
Autoturism RENAULT SYMBOL 1,5 dCI, car	Euro 3	1.500	281,056	20	50,90	61,80	75,40

Table 10: Centralizer with the minimum, medium and maximum values of noise levels measured in the passenger compartment of passenger cars with compression ignition (Diesel) engines, when driving through an urban area at a speed of 50 km/h

Type and make of vehicle	European pollution standard	Cylinder capacity (cm^3)	On-board kilometers (real km)	Age (years)	Sound values measured inside the passenger compartment dB(A)		
					Minium	Medium	Maximum
Autoturism RENAULT CAPTUR 1,5 dCI	Euro 5	1.500	87,400	5	53,00	62,90	75,30
Autoturism RENAULT SYMBOL 1,5 dCI	Euro 3	1.500	281,056	20	55,80	65,00	74,10

Table 11: Centralizer with the minimum, medium and maximum values of noise measured in the passenger compartment of cars with compression ignition engines (Diesel), while driving on the A1 - Sibiu highway

Type and make of vehicle	European pollution standard	Cylinder capacity (cm^3)	On-board kilometers (real km)	Age (years)	Sound values measured inside the passenger compartment dB(A)		
					Minium	Medium	Maximum
Autoturism RENAULT CAPTUR 1,5 dCI	Euro 5	1.500	87,400	5	68,00	73,40	80,20
Autoturism RENAULT SYMBOL 1,5 dCI	Euro 3	1.500	281,056	20	71,00	76,20	80,40

Table 12: Legend

Legal norm in Annex III of the Regulation on the sound level of motor vehicles, issued by the European Commission on April 16, 2014.	European Vehicle Pollution Standard	Maximum permissible sound limit value dB(A)	Normal values, not exceeding the legal limit
	Vehicles for the carriage of passengers of category M1 having a power to mass ratio ≤ 120 kW/1,000 kg	72	Values above the legal limit

Interpretation of the results obtained

a) Imitated noises in the passenger compartment of the Volkswagen Jetta, 1.4 TSI, Euro 6 car

In Fig 21 we present the graph of the evolution of the noise perceived in the passenger compartment of the Volkswagen Jetta 1,400 cm^3 TSI, Euro 6, car when driving on urban routes and on the highway.

The following data results from the analysis of the evolution of the noise in the passenger compartment of the Volkswagen Jetta, 1,400 cm^3 TSI, Euro 6 car:

- when driving along the urban route at a speed of 30 km/h, the minimum noise value = 56.10 dBA, the average value = 61.50 dBA, the maximum value = 77.70 dBA;
- when driving on the urban route at 50 km/h, the minimum noise value = 55,20 dBA, the mean value = 63,00 dBA, the maximum value = 75,30 dBA;
- when driving the route on the A1 - Sibiu highway, the minimum noise level = 67,10 dBA, the mean value = 73,20 dBA, the maximum value = 89,30 dBA.

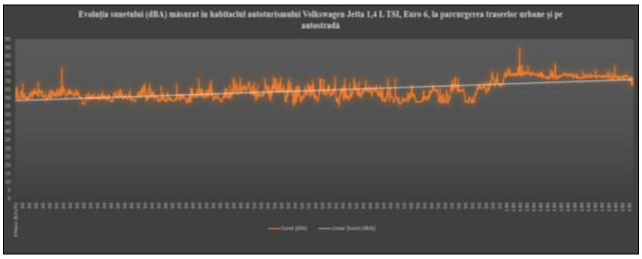

Fig 21: Evolution of the noise (dBA) received in the passenger compartment of the Volkswagen Jetta 1.400 cm^3 TSI, Euro 6 car, on urban and highway routes

Specific conclusions: The trend in the evolution of the interior noise of the Volkswagen Jetta 1,400 cm^3 TSI, Euro 6 car, on the two urban and highway routes is increasing. Noise levels in the passenger compartment increase with increasing speed.

When driving on the urban route at a speed of 30 km/h, the minimum and average values of the noise immission do not exceed the legal norm, which is 72 dBA. The maximum values exceed the legal norm, which ***confirms*** research hypothesis 1;

When driving on the urban route at 50 km/h, the minimum and average values of the immission noise do not exceed the legal norm. The maximum values exceed the legal norm;

When driving on the A1 - Sibiu highway, the minimum immission noise values do not exceed the legal limit. The maximum and average values exceed the legal norm, which ***confirms*** research hypothesis no. 2.

Passenger car noise decreases with decreasing urban traffic speed from 50 km/h to 30 km/h. The linear evolution of noise on the three routes shows a rapid increase in values.

b) Imitated noises in the passenger compartment of the Dacia Solenza 1.4 MPI, Euro 3 car

In Fig 22 we present the graph of the evolution of the sound received in the passenger compartment of the Dacia Solenza 1,400 cm^3 MPI, Euro 3 car, when driving on urban and highway routes.

From the analysis of the evolution of the sound received in the passenger compartment of the Dacia Solenza 1,400 cm^3 MPI, Euro 3 car, the following data result:

- when driving on the urban route at a speed of 30 km/h the minimum sound value = 59.20 dBA, the average sound value = 68.10 dBA, the maximum sound value = 83.30 dBA;
- when driving on the urban route at a speed of 50 km/h minimum sound value = 55,80 dBA, mean sound value = 70,60 dBA, maximum sound value = 85,60 dBA;
- when driving on the A1 - Sibiu highway at a speed of 130 km/h minimum sound level = 76,30 dBA, mean sound level = 81,10 dBA, maximum sound level = 85,50 dBA.

Specific conclusions: The trend in the evolution of the interior sound of the Dacia Solenza 1.400 cm^3 MPI, Euro 3 car, when driving on the two urban routes and on the highway, is increasing. The noise level in the passenger compartment increases with increasing speed.

When driving on the urban route at a speed of 30 km/h, the minimum and average values of the immissions do not exceed the legal norm. The maximum values of immission sound exceed the legal norm, which is 72 dBA, which ***confirms*** research hypothesis 1;

When driving on the urban route at 50 km/h the minimum and average values of immission sound do not exceed the legal norm. The maximum immission sound values exceed the legal norm;

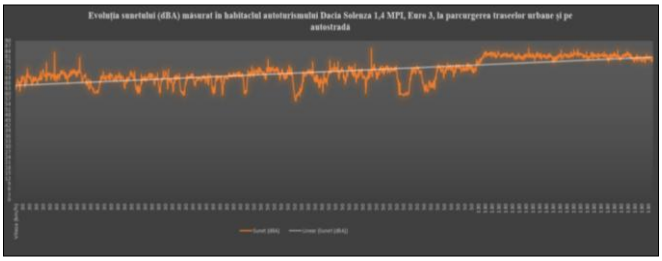

Fig 22: Evolution of the noise evolution (dBA) received in the passenger compartment of the Dacia Solenza 1.4 MPI, Euro 3 car, on urban and highway routes

When driving on the A1 - Sibiu highway at a speed of 130 km/h, all the values of the immission sound exceed the legal norm, which ***confirms*** the research hypothesis no. 2.

The noise emitted by the car in the passenger compartment decreases with the decrease of the traffic speed in urban environment from 30 km/h to 50 km/h. The linear evolution of the sound on the three routes has a rapid increase in values.

c) Imitated noises in the passenger compartment of the Renault Captur 1.5 dCI car

Fig 23 shows the graph of the evolution and interpretation of the noise received in the passenger compartment of the Renault Captur 1.500 cm^3 dCI, Euro 5 car, when driving on urban and highway routes.

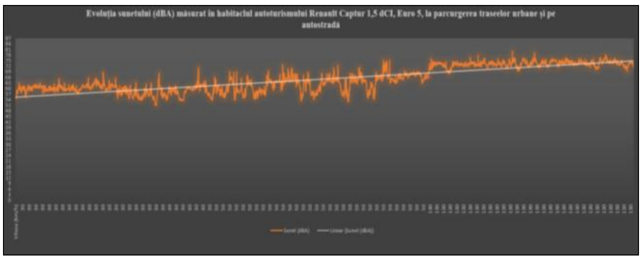

Fig 23: Evolution of the noise (dBA) received in the passenger compartment of the Renault Captur 1.5 dCI, Euro 5 car, during urban and highway route

The following data result from the analysis of the evolution of the noise in the passenger compartment of the Renault Captur 1.5 dCI, Euro 5 car:
- when driving along the urban route at a speed of 30 km/h, the minimum noise value = 51.00 dBA, the average value = 59.20 dBA, the maximum value = 71.30 dBA;
- when driving on the urban route at 50 km/h, the minimum noise value = 53,00 dBA, the mean value = 62,90 dBA, the maximum value = 75,30 dBA;
- when driving the route on the A1 - Sibiu highway, the minimum noise value = 53,00 dBA, the mean value = 62,90 dBA, the maximum value = 75,30 dBA.

Specific conclusions: The trend in the evolution of interior noise of the Renault Captur 1.5 dCI, Euro 5 car, on the two urban and highway routes is increasing. The noise level in the passenger compartment increases with increasing speed.
When driving on the urban route at a speed of 30 km/h, the levels of noise do not exceed the legal norm of 72 dBA, which does ***not confirm*** hypothesis no. 1 of the research.
When driving on the urban route at a speed of 50 km/h, the minimum and average values of the immission noise do not exceed the legal norm. The maximum values of the sound immission in the passenger compartment exceed the legal norm.
When driving on the A1 - Sibiu highway, the minimum immission noise values do not exceed the legal limit. The maximum and average values exceed the legal norm, which ***confirms*** research hypothesis no. 2.
The noise emitted by the car in the passenger compartment decreases with decreasing urban traffic speed from 50 km/h to 30 km/h. The linear evolution of noise on the three routes shows a rapid increase in values.

d) Imitated noises in the passenger compartment of the Renault Symbol 1.5 dCI, Euro 3 car

Fig 24 shows the graph of the evolution of the sound received in the passenger compartment of the Renault Symbol 1.5 dCI, Euro 3 car, when driving on urban and highway routes.

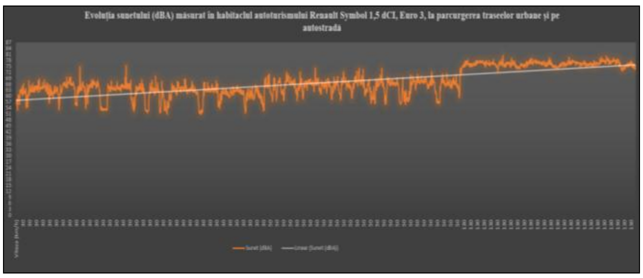

Fig 24: Evolution of the noise (dBA) received in the passenger compartment of the Renault Symbol 1.5 dCI, Euro 3, on urban and highway route

From the analysis of the evolution of the sound received in the passenger compartment of the Renault Symbol 1.5 dCI, Euro 3 car, the following data is obtained:
- when traveling the urban route at a speed of 30 km/h the minimum sound value = 50.90 dBA, the average sound value = 61.80 dBA, the maximum sound value = 75.40 dBA;
- when traveling on the urban route at a speed of 50 km/h minimum sound value = 55,80 dBA, mean sound value = 65,00 dBA, maximum sound value = 74,10 dBA;
- when driving on the A1 - Sibiu highway at a speed of 130 km/h the minimum sound value = 71.00 dBA, the average sound value = 76.20 dBA, the maximum sound value = 80.40 dBA.

Specific conclusions: The trend in the evolution of the sound in the passenger compartment of the Renault Symbol 1.5 dCI, Euro 3, on the two urban and highway routes is increasing. The level of interior noise of the car increases with increasing speed.
When driving on the urban route at a speed of 30 km/h, the minimum and average values do not exceed the legal limit of 72 dBA. The maximum values of immission sound exceed the legal norm, which ***confirms*** the research hypothesis no. 1;
When driving on the urban route at 50 km/h the minimum and average values of immission sound do not exceed the legal norm. The maximum immission sound values exceed the legal norm;
When driving on the A1 - Sibiu highway at a speed of 130 km/h, the minimum immission sound values do not exceed the legal limit. The maximum values and the average value of the sound immission exceeds the legal norm, which ***confirms*** the research hypothesis no. 2.
The noise emitted by the car in the passenger compartment decreases with decreasing traffic speed in urban environment from 30 km/h to 50 km/h. The linear evolution of the sound on the three routes has a rapid increase in values.

6. Conclusions

Environmental noise, in particular road traffic noise, continues to be an important environmental problem for millions of people in Europe, affecting their health and well-being, according to a report on environmental noise. Approximately 20% of Europe's population is exposed over the long term to noise levels that are harmful to health, i.e. around 100 million people in Europe. The data also indicate that policy objectives on environmental noise have not been achieved. In fact, based on the projections, the number of people exposed to noise is unlikely to decrease significantly in the future, due to urban sprawl and increased demand for mobility.
The speed of sound is strongly dependent on temperature, but also on the medium through which a sound wave propagates.
At speeds faster than the speed of sound (supersonic speed), an observer in front of the moving sound source will receive the waves in the opposite direction to the direction in which they are produced. By compressing the air in the forward direction, a wave is generated which is not periodic in character, but represents only a compression domain propagating with the speed of sound. Such a wave is called a shock or ballistic wave. They cause the sensation of a strong shock. These waves occur, for example, with bullets, projectiles or jets.
Sound propagation velocity refers to the speed at which sound waves travel through a specific material, usually measured in centimeters per microsecond or meters per second. Knowing the speed of sound in different materials allows us to better understand and analyze the characteristics and quality of these materials.
By accurately measuring and analyzing the speed of sound, we can better assess the quality of the environment, structure or material being analyzed. In this way, we can detect defects in their types and composition. Sound velocity

serves as a powerful tool in non-destructive testing, allowing us to make accurate and reliable judgments.

By measuring the speed of sound, we can detect flaws, cracks or other potential problems in materials. In ultrasonic testing, the accuracy and reliability of sound velocity is crucial in determining the integrity of materials.

Sound propagation speed can be used to identify the type and composition of materials. Sound speed in different materials is influenced by factors such as density, elasticity and molecular structure. By measuring the speed of sound, we can infer material properties and perform further analysis.

Sound speed refers to how fast sound waves propagate through a medium. It depends on the properties of the medium such as density, elasticity and temperature. In general, sound travels faster in denser and more elastic media.

The scientific paper has achieved the purpose for which it was written. Our research has shown that, no matter how well soundproofed/ sound insulation a car passenger compartment may be, at high speeds (e.g. on the highway), or at high engine speeds (e.g. at speeds of 30 km/h in an urban environment, when a higher gear is not allowed from the point of view of correct engine operation because engine under-torque occurs and on the highway when car engines are over-torqued), cars with inadequate sound insulation, the values of the sounds imitated in the passenger compartment exceed the maximum permissible European norm of 72 dBA (this is the maximum permissible value of the sounds and noises imitated in the passenger compartment, as allowed by the European legislation, for the type of cars we used in the experiment). It is very important that these values of the sounds and vibrations that are imitated in the passenger compartment are brought as close as possible to this value or to the normal value of the conversation threshold (65 dBA - see Fig 4), in order to prevent the road users, as well as other people outside the passenger compartment (on the street, where the sounds propagate freely in the environment outside the vehicle), from becoming ill.

Exceedance of the maximum permissible sound and noise thresholds regulated by European legislation for the cars used in our research was demonstrated in practice by this experimental research as follows:

a.) Noise immission in the passenger compartment of cars with spark ignition engines. Analyzed in terms of average values, for the noise emissions that are regulated by legislation, the situation is as follows. Cars that exceeded the legal norm of 72 dBA in the extra-urban environment when driving on the highway: Volkswagen Jetta 1.4 TSI, Euro 6 car (73.20 dBA) and Dacia Solenza 1.4 MPI, Euro 3 car (81.10 dBA).

The Dacia Solenza 1.4 MPI, Euro 3 car is the most polluting vehicle in terms of noise levels in the passenger compartment. When driving on the highway, the minimum, average and maximum values were exceeded (minimum = 76.3 dBA; average = 81.10 dBA; maximum = 85.5 dBA).

The peaks of noise immission in the passenger compartment in the urban environment, when traveling the route at a speed of 30 km/h, were reached by the cars: Volkswagen Jetta 1.4 TSI, Euro 6 car = 77.7 dBA; Dacia Solenza 1.4 MPI, Euro 3 car = 83.3 dBA.

The peaks of noise levels in the passenger compartment in the urban environment, when driving at a speed of 50 km/h, were reached by the following cars: Volkswagen Jetta 1.4 TSI, Euro 6 car = 75.3 dBA; Dacia Solenza 1.4 MPI, Euro 3 car = 85.6 dBA.

Passenger compartment noise peaks in the extra-urban environment, when driving on the highway at a speed of 130 km/h, were reached by the cars: Volkswagen Jetta 1.4 TSI, Euro 6 car = 89.3 dBA; Dacia Solenza 1.4 MPI, Euro 3 car = 85.5 dBA.

In the case of gasoline-engined passenger cars, from the analysis of the data presented above, the level of noise pollution in the passenger compartment is determined by the engine speed, the type and profile of tires, the condition and degree of deterioration of the road surface, the state of maintenance, the noise level produced by the elements and transmission components, the age in years (moral wear and tear) and physical wear and tear.

By reducing the driving speed in urban areas from 50 km/h to 30 km/h, the average noise levels in the passenger compartment ***reduced*** for the following cars: Volkswagen Jetta 1.4 TSI, Euro 6 car (from 63.00 dBA to 61.5 dBA); Dacia Solenza 1.4 MPI, Euro 3 car (from 70.60 dBA to 68.1 dBA).

By reducing the driving speed in urban areas from 50 km/h to 30 km/h, the average noise levels in the passenger compartment did ***not increase*** for any gasoline-engined car.

b.) Noise immission in the passenger compartment of passenger cars with compression ignition (Diesel) engines.
Analyzed through the prism of the average values for the noise levels that are regulated by the legislation, the situation is presented below. In the extra-urban environment, the following cars exceeded the legal norm of 72 dBA when driving on the highway: Renault Captur 1.5 dCI, Euro 5 car (73.4 dBA) and Renault Symbol 1.5 dCI, Euro 3 car (76.2 dBA).

Passenger compartment noise peaks in the urban environment at 30 km/h were reached by the Renault Symbol 1.5 dCI, Euro 3 car (75.4 dBA).

Passenger compartment noise peaks in the urban environment, when driving at 50 km/h, were reached by the following cars: Renault Captur 1.5 dCI, Euro 5 car (75.3 dBA) and Renault Symbol 1.5 dCI, Euro 3 car (74.10 dBA).

The passenger compartment sound peaks in the extra-urban environment, when driving on the highway at 130 km/h, were reached by the following cars: Renault Captur 1.5 dCI, Euro 5 car (80.2 dBA) and Renault Symbol 1.5 dCI, Euro 3 car (80.4 dBA).

By reducing the traffic speed in urban areas from 50 km/h to 30 km/h, the average noise levels in the passenger compartment ***reduced*** for the following cars: Renault Captur 1.5 dCI, Euro 5 car (from 62.9 dBA to 59.2 dBA) and Renault Symbol 1.5 dCI, Euro 3 car (from 65.00 dBA to 61.8 dBA).

By reducing the urban driving speed from 50 km/h to 30 km/h, there was ***no increase in the average passenger compartment noise*** levels for any car.

In the case of both gasoline and diesel cars, from the analysis of the data presented above, the level of noise pollution in the passenger compartment is determined by: the engine speed level, the type and profile of tires, the condition and degree of deterioration of the road surface, the state of maintenance, the noise level produced by the elements and transmission components, the age in years (moral wear) and physical wear.

In cars with diesel engines (Diesel), the noise in the passenger compartment is higher as a result of the vibrations and noises specific to these engines in operation. This is due to the ignition principle, the compression ratio (16.1 - 20.1:1 in compression-ignition (Diesel) engines compared to 9.5 - 15:1 in spark-ignition (gasoline) engines), the lower engine speed, and the higher power compared to gasoline engines.

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