# The assessment and evaluation of low-frequency noise near the region of infrasound

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**Abstract**

**The main aim of this paper is to present recent knowledge about the assessment and evaluation of low-frequency sounds (noise) and infrasound, close to the threshold of hearing, and identify their potential effect on human health and annoyance. Low-frequency noise generated by air flowing over a moving car with an open window was chosen as a typical scenario which can be subjectively assessed by people traveling by automobile. The principle of noise generated within the interior of the car and its effects on the comfort of the driver and passengers are analyzed at different velocities. An open window of a car at high velocity behaves as a source of specifically strong tonal low-frequency noise which is generally perceived as annoying. The interior noise generated by an open window of a passenger car was measured under different conditions: Driving on a highway and driving on a typical roadway. First, an octave-band analysis was used to assess the noise level and its impact on the driver's comfort. Second, a fast Fourier transform (FFT) analysis and one-third octave-band analysis were used for the detection of tonal low-frequency noise. Comparison between two different car makers was also done. Finally, the paper suggests some possibilities for scientifically assessing and evaluating low-frequency sounds in general, and some recommendations are introduced for scientific discussion, since sounds with strong low-frequency content (but not only strong) engender greater annoyance than is predicted by an A-weighted sound pressure level.**

*Keywords:* *Annoying, assessment, health, low-frequency noise, measurement*

## Introduction

Noise is one of the major environmental hazards of modern society originating from a wide variety of sources, including traffic (air, road, rail), industrial facilities, or social activities.[1,2] Low-frequency noise (LFN) and/or vibration can be also generated by explosions, aerodynamic impact, machines installed in buildings or industrial structures and/or in the vicinity of these structures, wind turbines, technological processes such as forging, shearing, and forming, chemical processes, transportation, construction activity, and other sources of unwanted low-frequency excitation. The adverse health effects of community noise cause a serious public health problem, interference with speech communication, disturbance of rest and sleep, psychological and performance effects, effects on behavior, and subjective annoyance and interference with intended activities.[1-3] Besides the psychosocial effects of community noise, there is concern about the impact of noise on the cardiovascular system.[4,5]

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The evidence on noise exposure and health varies across health outcomes and, although there have been considerable research achievements in this field, there are still significant gaps that need to be filled. These include the studies of low-frequency sounds.

Low-frequency sound, where the frequency ranges from approximately (10 to 160) Hz, has been recognized as a special environmental noise problem, particularly to sensitive people in their homes.[6] As a background noise in urban and work environments, it is emitted from many artificial sources such as road vehicles, aircraft, and air movement machinery including wind turbines, compressors, diesel engines, machines with large rotating and/or reciprocating motion, ventilation or air-conditioning units, etc., In addition to the objective effects, LFN could also cause noise annoyance and influence mental performance.[7,8]

Relatively little research has been carried out in order to establish which effects are specifically caused by the LFN emitted from various sources, e.g. from an open window in a moving car, vibration of pipes, standing waves that are created by traffic noise (especially from diesel engine vehicles such as lorries, buses, and trains), or by sound which is generated by the sources inside of enclosed spaces [vibration of building equipment, heating, ventilation, and air-conditioning (HVAC), music noise pollution, etc.], and how to assess and evaluate this LFN in enclosed spaces.[9-17] Sound with very long wavelength may be perceived as pulsations and fluctuations in ear pressure (primary noise), caused by rattling balcony glass, windows, doors, or furniture (secondary noise), which may be difficult to distinguish from structural vibrations.[18]

Both forms of noise can cause disturbance, particularly during mental work, when driving, relaxing, etc., LFN can be more noticeable indoors, which is why it is often associated with attention reduction, sleep disturbance, adverse effects on health, etc., with the possibility of standing wave or partial standing wave generation in enclosed spaces.[19] Another problem is that LFN travels farther than higher-frequency noise, so the source is often more difficult to trace. A large proportion of sound is generated by mechanical vibration of a solid component in a building structure and/or by equipment in the building.[20] The mechanical energy involved has often been transmitted from remote mechanical or acoustical sources by means of audio frequency vibration waves propagating through connected structures, which is typical structure-borne sound. The subject of structure-borne sound is far more complex than that of air-borne sound in otherwise quiescent air. Whereas air can support only longitudinal acoustic waves, two fundamental forms of vibration waves can exist in unbounded elastic solids because they can support shear stress. This paper focuses, in detail, on LFN generated by an open car window.[16]

The methods and procedures described in this paper are intended to be applicable to LFN originating from various sources, whether individually or combined, which contribute to total exposure. Currently, the evaluation of LFN annoyance seems to be best met by adopting the adjusted Z-weighted equivalent continuous sound pressure level or the minimal C-weighted one can observe that sounds of low-frequency content cause greater annoyance than is assessed by A-weighted sound pressure levels, particularly, at higher levels.[17-19]

The goal of this study is to contribute to the international harmonization of methods toward the description, measurement, assessment, and evaluation of low-frequency sounds from all external and internal sources within enclosed spaces and to provide some background for public and professional discussions on how to more precisely describe, assess, and evaluate low-frequency sounds in enclosed spaces. Based on the principles described in this paper and the principles introduced in Ref. [19], a basis can be set for further research in this area.

## Methods

### Measurement

The LFN generated by open window of a moving car is very strong and a good representative example of why it is necessary to assess and evaluate through more precise methods than that are being used until recently. The experiment can also be easily carried out by opening the rear window at higher car speeds, where each attending person can subjectively assess the effects of this noise on their own comfort and health.

Replenishing the air within a moving car can be done in a few ways. Either the built-in air-conditioning can be used or the air can be exchanged by opening the windows. Many drivers prefer the second option due to some reported effects of air-conditioning on health. Negative effects on human beings is usually caused by a sudden change in temperature and humidity (thermal shock) and can lead to a series of health complications. According to doctors of various specialties, respiratory infections are facilitated in these conditions and the entire cardiovascular system is compromised, increasing the risk of heart attack and stroke.[21,22] However, opening the windows, and so exchanging the air, leads to a reduction of acoustic comfort for the driver and passengers, especially due to the introduction of LFN. This effect is observed primarily on highways, or high-speed roads out of the city. In a city, the effect of aerodynamically induced noise is insignificant due to low speeds. Under certain conditions, this specific acoustic vibration can have a negative impact on the health of the driver and/or passengers.[23,24]

To analyze the noise exposure at the lower frequency limit of sound perception, i.e. around 16 Hz, which is generated when opening the car windows, the sound level analyzer (Bruel and Kjaer 2250) was used. To identify the energy dominant tonal noise more precisely, the fast Fourier transform (FFT) analysis was carried out using the PULSE analyzer, Dyn-X, FFT, M1 3560-B-X10 on a Bruel and Kjaer platform. The methodology presented in the article can also be applied for other sources of very low frequency sounds, such as air-conditioning systems, boiler systems, large low-frequency diesel engines and/or idling diesel engine vehicles (cars, buses, lorries), loud music in neighboring rooms, etc.[18-20,25]

The noise level was measured inside two different passenger cars: NISSAN TIIDA (model year 2009) and LEXUS (model year 2008 LS 460). During the measurements, the car was driven on Slovak highways with minimal traffic, i.e. to minimize the influence of other sources of noise from the passing or nearby cars. The measurements were done at various car speeds ranging from (70 to 140) km/h (maximum 150 km/h) and on roads chosen to be as homogeneous as possible. Another variable parameter in the analysis was how much the window was opened, where three cases were compared: All windows closed, window partially open (approximately 5 cm), and window fully open.

It was concluded that neither the engine nor the rolling noise from the tyres influence the strong LFN induced by opening the window. The noise was measured at the ear level of the driver, i.e. the microphone of the PULSE platform and sound level meter analyzer was positioned close to the head, in order to analyze the effect of the noise on the driver's ear while driving the car, as shown in Figure 1.

## Results and Discussion

### Repeatability and reproducibility of measurements

The FFT measurements showed that the measured data were consistent and that the dispersion of peak values was a maximum of 3 dB, as presented in Figure 2. These differences can be caused by the speed variation in the car and/or variation of the air flow speed around the car by changing wind direction. Similarly, the frequency varied up to 1 Hz, at constant speed, due to the real conditions of air flow during measurements.

From the FFT analysis, it is obvious that when the window is open, strong tonal very LFN is generated in the lower limits of human sound perception. The non-weighted values (so-called Z-weighting) exceeded 115 dB, depending on the car speed. These levels of sound pressure are close to the threshold of pain.

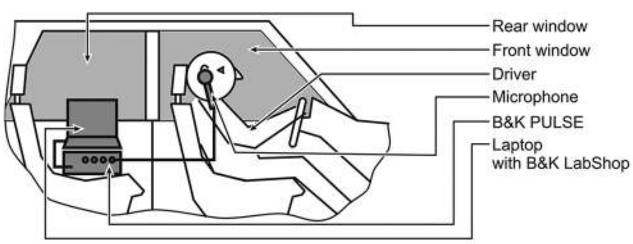


**Figure 1: Schematic of the measurement setup inside of a passenger car while driving**

### Weighting functions

The utilization of Z-weighting or linear weighting (i.e. no loss of acoustic energy in regards to the auditory organ) shows the exposure of the human beings directly to this noise, regardless of the sensitivity of his/her ears.

Currently, there is a discussion about the evaluation of LFN at high sound pressure levels, since the A-filters, which are used most often, do not correctly reflect the influences of this energy on the health and comfort of human beings.[9-15,19,26,27] Therefore, in analyzing the measured spectra in the article, the A-, C- and Z-weightings are presented.

Frequency analysis of the investigated low-frequency region with application of the above weightings is presented in Figure 3, where Figure 3a shows the results for constant speed and Figure 3b shows the results for different speeds of the passenger car.

The sensitivity (perception) of the human ear at low frequencies is much lower; therefore, the measured results also, weighted using the A- as well as C- or Z-weightings, differ significantly. The sound energy difference between C- and A-weightings is approximately 32000-fold and between Z- and A-weightings is up to 160000-fold. Even keeping in mind that the sound energy is negligible compared to the other sources of energy, the presented differences in acoustical weighting should not be ignored when evaluating the effects of low-frequency sounds on human beings. From a health point of view, each type of energy has the ability to do work – either negative or positive. However, there exists a limit of positive and negative effects on human organisms, and so, this limit should be set exactly or estimated in the most precise way.

In Figure 3b, it is seen that the frequency of noise generated by air flow in the interior of a car (open window) slightly changes while the frequency of noise which depends on the

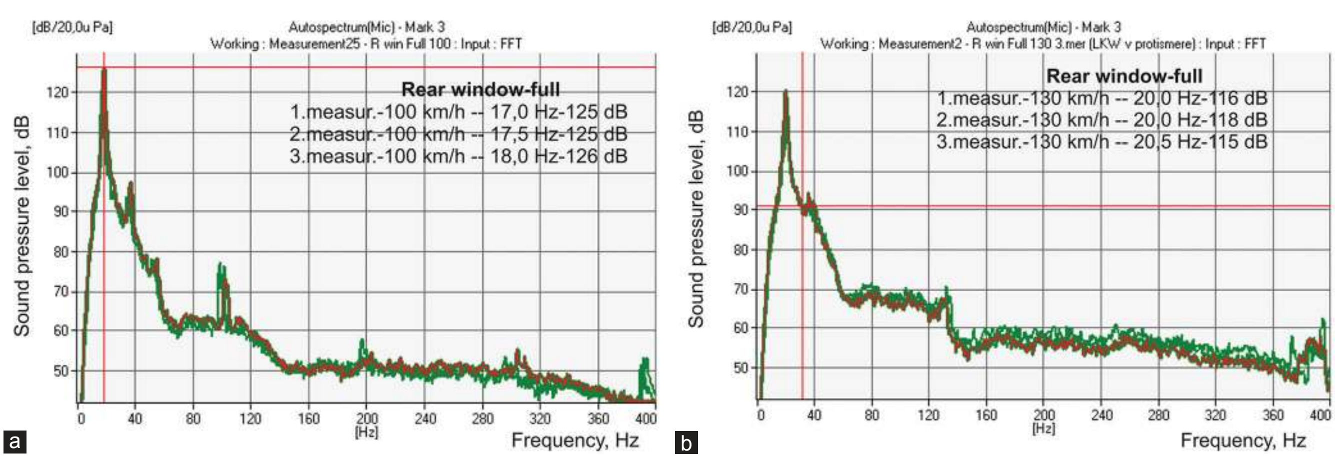


**Figure 2: FFT analysis of the generated noise in the car interior – three measurements with two different car speeds: (a) 100 km/h and (b) 130 km/h**

speeds of engine changes more rapidly with the change of the car velocity at the same speed gear. The A-weighted sound pressure level of the automobile engine at the open window is masked by LFN generated by air flow and has no influence on the assessment and evaluation of the interior car noise, and it has no effect on the human (in this case, driver and passengers) comfort and health.

## Influence of window opening

The behavior of A- and C-weightings of the analyzed, strong, very LFN is presented in Figure 4a and b. Again, there are significant differences between the A- and C-weightings compared to the measured cases with a fully and partially opened rear (driver's side) window (the same window used) within the frequency band of interest (11.2-22.4) Hz for this type of noise.

The reduction of acoustic level, applying C- and A-weightings, with the same maximal window opening is up to 46 dB, whereas with a partially open rear window, the maximal noise levels are shifted to a higher frequency when A-weighting is used, even though the low-frequency content of sound energy is significantly higher than the background noise (i.e. all windows closed), as shown in Figure 4b. It is important to notice that the subjective energetic perception (action) of the driver to the noise was significantly higher than what was measured using the A-weighted sound pressure level. This perception was reflected more so when using C-weighting. From Figures 4 and 5, it is clear that at a partially open window (gap 5 cm), no tonal frequency exists.

## Influence of car speed

A similar behavior of the frequency spectra was analyzed at higher car speeds, where the difference between C- and A-weightings was just 2 dB lower, i.e. 44 dB, and also for this set of measurements, with partially open window, the characteristic amplitudes of tonal frequencies were shifted to higher frequencies [Figure 5a and b]. At higher car speeds, two specific tonal frequencies of a mechanical nature (engine) were identified. With open window, these tonal frequencies are masked by the source of strong aerodynamic LFN.

The variation of A-weighted sound pressure level (SPLA),

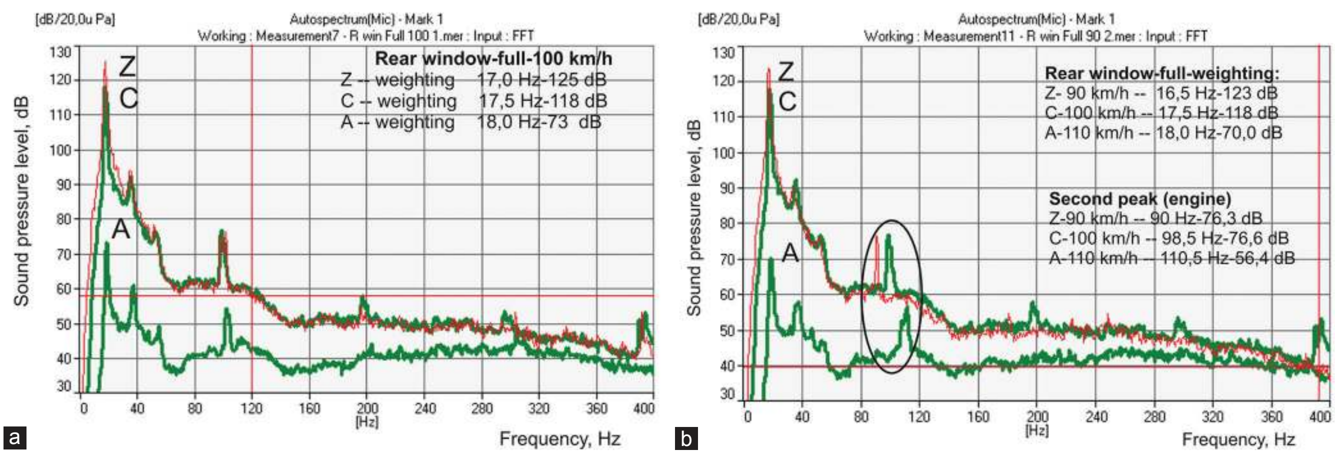


**Figure 3: Comparison of energy using Z-, C-, and A-weightings of the same acoustic signal at different car speeds: (a) 100 km/h and (b) different speeds**

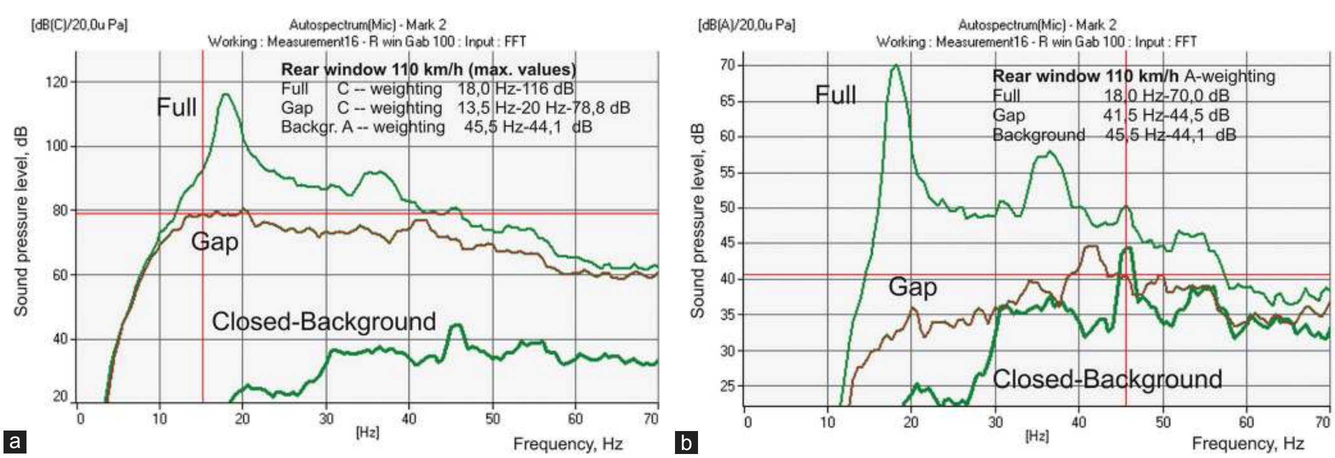


**Figure 4: Comparison of energies using (a) C-weighting and (b) A-weighting of the same acoustic signal at a constant car speed of 110 km/h**

C-weighted sound pressure level (SPLC), Z-weighted sound pressure level (SPLZ), and also frequency variation as a function of car speed is presented in Figure 6. From Figure 6, it is obvious that the highest energy values of tonal LFN with a fully opened window occur at velocities from (80 to 130) km/h. The same noise situation was observed in the other passenger car (LEXUS).[16] The measured levels are close to the threshold of pain. Non-negligible sound energy values were present at both lower and higher car speeds. A significant difference in energy values was observed when an acoustic weighting was used, i.e. an artificial correction of human exposure with the exception of different sound perception at the defined frequency bandwidth. From this, the question can be raised whether or not it is more correct to use Z- or minimal C-weighting in the evaluation of energy from powerful acoustic vibration in very low frequency bands.

In Figure 6, it can be seen that a variation of the car speed and the corresponding characteristic frequency of the tonal noise is shifted from the region of infrasound into the range of audible sound. In this frequency interval is generated very strong sound energy, which has negative effects on the auditory organ and also potential negative effects on the human organism.

Again, it needs to be emphasized that the perception of strong LFN was much more significant than at an A-weighted level. The perception corresponded more to the C-weighted level, probably also because of the fact that C-weighting is close to the threshold of pain. Furthermore, the analyzed low-frequency, energy-rich sound is close to the threshold of pain. On increasing the car speed above 130 km/h, the specific tonal LFN generated by air entering the interior of the car decreased and the noise induced from tyre and aerodynamic effects became more dominant.[17]

## Comparison of cars

In the interior of the LEXUS, measurements were carried out following the same methodology as in the previous analysis, but in this case, the third-octave Constant Percent Bandwidth (CPB) analysis using A-weighting as well as C-weighting was measured at two car speeds, i.e. at 130 km/h [Figure 7a] and at 150 km/h [Figure 7b]. Even though different cars were used, this analysis shows that in the interior of the car, the generation of significant LFN is induced. This phenomenon is similar to the one analyzed in the previous section. This significant tonal noise, with center frequency of 20 Hz, can be identified from Figure 7a, i.e. in the third-octave band CPB analysis, and is dominant in the interior of the automobile.

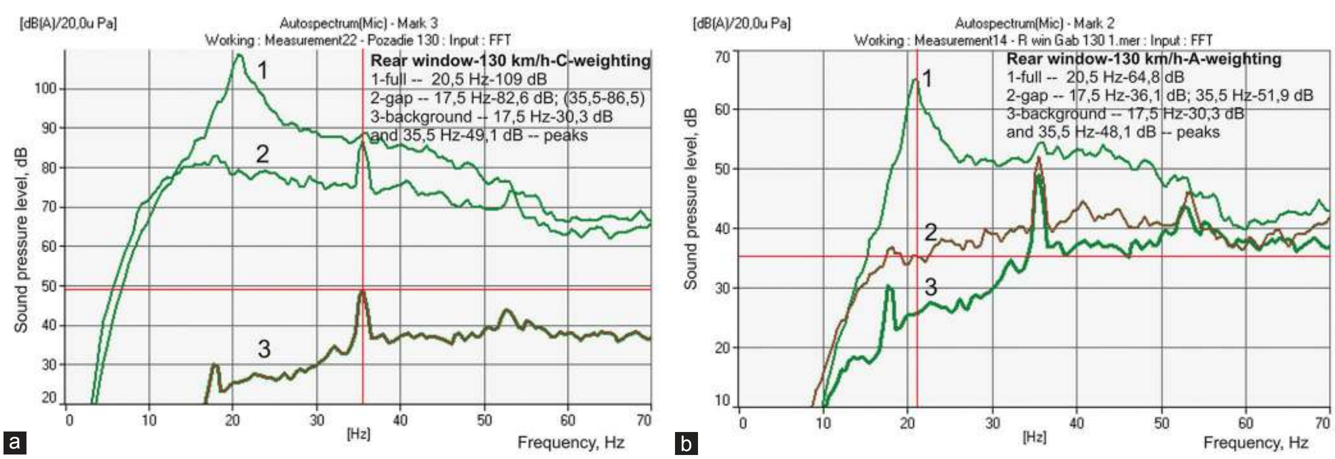


**Figure 5: Comparison of energies using (a) A-weighting and (b) C-weighting of the same acoustic signal at a constant car speed of 130 km/h**

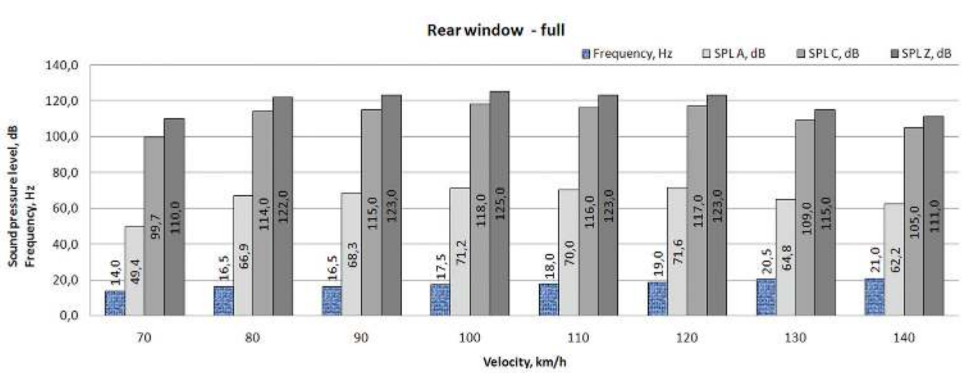


**Figure 6: The levels of A-, C-, and Z-weighted sound pressure and variation of the frequency as a function of car speed**

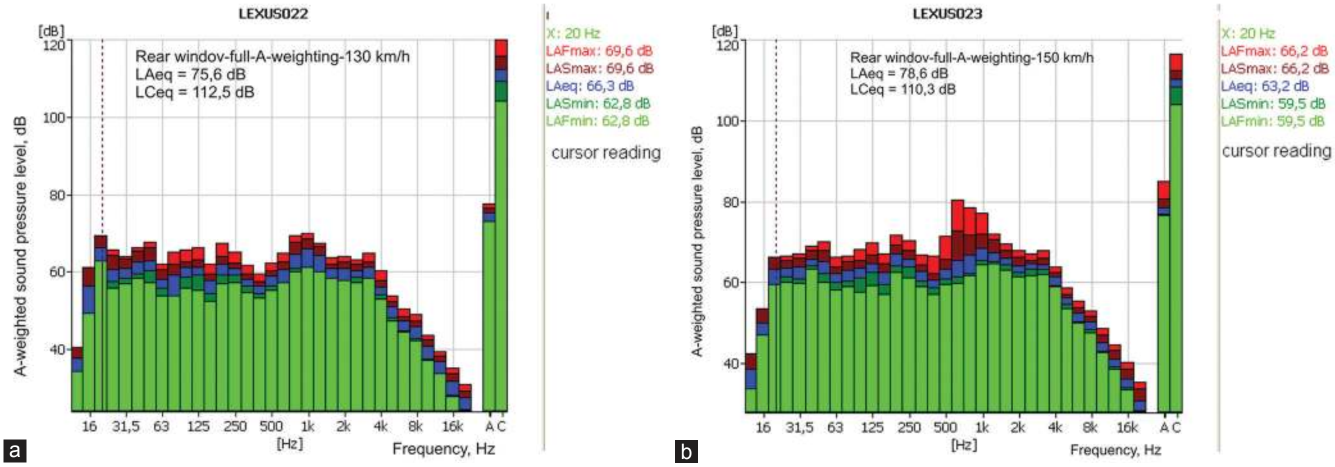


**Figure 7: Third-octave analysis of the A- and C-weighted sound pressure level of the same acoustic signal with car speeds of (a) 130 km/h and (b) 150 km/h**

Analogically to the previous measurements (inside of the NISSAN), the tonal frequency varied with the car speed. Similarly, the A-weighted sound pressure level measured in the LEXUS corresponded to that measured in the NISSAN.

On increasing the speed above 130 km/h, the specific tonal LFN generated by air entering/exiting the interior of the car decreased, whereas the noise induced from tyre and aerodynamic noise generated by air flow in the outside space of a car body became dominant [Figure 7b].

## Effects on humans

Under certain conditions, this specific LFN can have a negative impact on the health of the driver and/or the passengers. It can lead to annoyance, tiredness, and lower attention to the situation around the car, thus reducing the attention and awareness of the driver. This means that the specific noise can have a negative impact on driving safely, especially in cases of long-distance drives.[6,17] Noise exposure also has been known to induce tinnitus, hypertension, vasoconstriction, and other cardiovascular adverse effects.[28]

In terms of specific influences, it is hearing fatigue which can lead to the damage of the aural system.[23] The elevated sound levels cause trauma to the cochlear structure in the inner ear, which gives rise to irreversible hearing loss.[29] Human bodies exposed for a long term to higher levels of this specific noise can have constriction of arterial blood vessels and elevated blood pressure; in this case, it appears that a certain fraction of the population is more susceptible to vasoconstriction. This may result because annoyance from the sound causes elevated adrenaline levels, triggering narrowing of the blood vessels (vasoconstriction), or may arise independently through medical stress reactions. Other effects of high exposure to LFN (sound) levels are increased frequency of headaches, fatigue, stomach ulcers, and vertigo.[4,5,30]

The influence of noise on blood pressure as well as the consequent development, or even worsening, of hypertension is generally known. While assessing the risk factors of noise on blood pressure, it was found that noise affects blood pressure at levels higher than $L_{aeq}$ > 85 dB. Based on the results presented in Ref. [30], the relative risk of infarct at the sound level pressure $L_{aeq}$ = (62-65) dB is between 1.05 and 1.3 and at levels $L_{Aeq}$ > 66 dB is between 1.1 and 1.6, which corresponds to an increased risk of harm by 10-60%.[28] More recent studies have suggested that A-weighted sound pressure levels of 50 dB at night may also increase the risk of myocardial infarction by chronically elevating cortisol production.[31,32]

## Assessment and evaluation of noise with strong low-frequency content

To be of practical use, any method of description, measurement, and assessment of outdoor and indoor noise sources acting in enclosed spaces must be related in some way to what is known about human response to noise. Many adverse consequences of outdoor and indoor noise sources grow as they intensify, but the precise dose–response relationships involved continue to be the subject of scientific debate. In addition, it is important that all methods used should be practicable within the social, economic, and political climate in which they are used. For these reasons, there is a very large range of different methods currently in use around the world for different types of noise, and this creates considerable difficulties for international comparison and understanding.

Researchers have found[33] that when people are exposed to infrasound under laboratory conditions, they may experience difficulties in performing mental work, as well as a general sense of discomfort. As the intensity increases, dizziness, nervous fatigue, nausea, and loss of balance are experienced by the same individuals. Another study[29] on hearing response to the frequency interval from (10 to 20)

Hz reports that the depression of upper limit of hearing (as measured by the number of seconds a tuning fork was heard) and the change in hearing sensitivity during several minutes where the temporary threshold shift occurred at around 4 kHz was up to 22 dB. Where threshold shifting occurs, it has been observed that the hearing level returns to its original level rather quickly. The US Environmental Protection Agency (EPA) recommends[34] a threshold level of 120 dB up to 16 Hz as the upper level of exposure to infrasound.

It must be kept in mind that low-frequency sounds essentially have higher energy than the sounds at mid and higher frequencies. In the measurements, the strong low-frequency sound on the boundary of hearing is characterized by an unpleasant, pulsating pressure on the ear drum. The long-term exposure of the energy-rich, low-frequency sounds can damage human health, affecting not only the hearing organ but also the functionality of other organ systems such as the central nervous system. Therefore, it is important to improve the criteria for assessing energy-rich, low-frequency sounds, so that the influences of sound energy on human health and comfort are assessed correctly. From the experiment presented here and the citied literature, it can be concluded that for energy-rich, low-frequency sounds (including infrasound), the following are suggested for further scientific discussion:

a. The frequency range of interest appears to be approximately from (10 to 25) Hz, but experiments show that the frequency range can be expanded minimum up to 100 Hz.[18,20] In the range below about 20 Hz, some countries use G-weighting to assess sound. Above 15 Hz, several countries use an octave-band or a one-third octave-band analysis between 16 Hz and 100 Hz and do not use A-weighting sound pressure level in the same way as it is used to assess mid- and high-frequency sound[9,12,26,27]
b. The strong low-frequency power content of sounds often contains tonal components, and therefore, it is more suitable to use one-third octave-band analysis or FFT analysis (which is better) in the frequency range from 10 to 100 Hz for the assessment of these types of sounds
c. For the assessment of sounds with strong low-frequency power content, in the frequency range from (10 to 100) Hz, it is more logical to use Z- or C-weighting rather than A-weighting
d. In the assessment criteria of LFN, it is important to consider measurements inside of an enclosed space rather than outside of the environment due to the presence of standing waves (room resonances at low frequencies) in that enclosed space.[18,19]

The limit values for sound (noise) of very low frequencies near the region of infrasound may be the topic of scientific discussion and should be a maximum value of 120 dB, as recommended by the EPA[34], or lower. The frequency range, weighting, frequency analysis, and space conditions are suggested earlier.

## Conclusions

From the experiments, and even from the personal participation of the investigators in the experiments, the energy from strong sounds (but not only strong sounds) of low-frequency content cannot be correctly evaluated using A-weighting SPL. The main reason is that this filter artificially attenuates the energy severity of the sounds acting on human beings. We must keep in mind that sound energy has a negative influence on our hearing. Therefore, the relatively strong sound energy exposure requires the application of Z- or C-weighting, in which the SPLs are in closer agreement with the threshold of pain. The results and analysis show that the experiments are closer to the evaluation methodology used in other, more developed countries. It can be concluded that sound energy from weaker, low-frequency acoustic waves can also cause the generation of standing waves (resonance within enclosed spaces), and therefore amplify the energy exposure on human beings. The presented recommendations for the evaluation of low-frequency acoustic waves (sound and infrasound) in enclosed spaces are intended to contribute to the current knowledge about noise evaluation, and also act as a stimulus for the scientific community, since the correct evaluation of this type of noise can help reduce potential adverse health effects and increase the comfort of human beings. Of course, the aforementioned assessment and evaluation of strong low-frequency sounds (but not limited to only strong LFN) is up for further scientific debate and the frequency range could be wide, up to approximately 100 Hz or up to 160 Hz.[20] On the other hand, weak low-frequency sounds can create situations of essentially increasing the level value in enclosed spaces that may be hard to predict from outdoor measurements. Therefore, the measurements inside of enclosed spaces that best represent the noise in this space prefer this type of measurements in terms of human annoyance.[19]

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