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INSTITUTE OF AUTOMOTIVE ENGINEERING

ÚSTAV AUTOMOBILNÍHO A DOPRAVNÍHO INŽENÝRSTVÍ

NOISE GENERATOR FOR ELECTRIC CARS

GENERÁTOR HLUKU PRO EV VOZIDLA

BACHELOR'S THESIS

BAKALŘSKÁ PRÁCE

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Assignment Bachelor's Thesis

Institut:	Institute of Automotive Engineering
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As provided for by the Act No. 111/98 Coll. on higher education institutions and the BUT Study and Examination Regulations, the director of the Institute hereby assigns the following topic of Bachelor's Thesis:

Noise generator for electric cars

Brief Description:

The silence of electric cars is both a great advantage and a disadvantage. In urban traffic, this can lead to collisions with pedestrians who can't hear the approaching vehicle. A sound generator can help to eliminate this disadvantage, but must not be an unnecessary burden on the overall energy balance of the vehicle.

Bachelor's Thesis goals:

Legislative requirements
A research of different approaches to this issue by automotive companies
Assessment and possible design of an innovative approach

Recommended bibliography:

STONE, Richard. Introduction to internal combustion engines. 3rd edition. Warrendale, Pa.: Society of Automotive Engineers, 1999. 641 s. ISBN 0768004950.

Deadline for submission Bachelor's Thesis is given by the Schedule of the Academic year2022/23

In Brno,

L. S.

prof. Ing. Josef Štětina, Ph.D. Director of the Institute	doc. Ing. Jiří Hlinka, Ph.D. FME dean

ABSTRAKT

Tato bakalářská práce se zabývá mnohostrannými aspekty generování hluku u elektrických vozidel. Prozkoumává předpisy, průmyslové postupy a představuje inovativní modely generování hluku, které posouvají naše porozumění této se objevující problematice. Výsledky výzkumu mohou vést k vývoji tišších a udržitelnějších elektrických vozidel, přispívajících k pozitivnímu uživatelskému zážitku a harmonickému soužití s životním prostředím.

KLÍČOVÁ SLOVA

Elektrická vozidla, hybridní vozidla, generování hluku, emise hluku.

ABSTRACT

This bachelor thesis deals with the multifaceted aspects of noise generation in electric vehicles. By exploring regulations, industry practices, and presenting innovative noise generation models, it advances our understanding of this emerging issue. The research findings can guide the development of quieter and more sustainable electric vehicles, contributing to a positive user experience and a harmonious coexistence with the environment.

KEYWORDS

Electric vehicles, Hybrid vehicles, Noise generation, Noise emissions.

BIBLIOGRAPHY

Sleiman, Adham. Generátor hluku pro EV vozidla. Brno, 2023. Bakalářská práce. Vysoké učení technické v Brně, Fakulta strojního inženýrství, Ústav automobilního a dopravního inženýrství. Vedoucí práce Jiří Bazala. Dostupné také z: SLEIMAN, Adham. Generátor hluku pro EV vozidla. Brno, 2023. Dostupné také z: https://www.vut.cz/studenti/zav-prace/detail/150001.

ČESTNÉ PROHLÁŠENÍ

Prohlašuji, že tato práce je mým původním dílem, zpracoval jsem ji samostatně pod vedením Jiří Bazala a s použitím informačních zdrojů uvedených v seznamu.

V Brně dne 26. května 2023 ……………..…………………………………………………..

Adham Sleiman

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I would like to thank my supervisor Ing. Jiří Bazala for his advices, patience and support throughout this thesis.

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ACRONYMS	DESCRIPTION
EV	Electric vehicle
AVAS	Acoustic vehicle alerting system
MAVAS	Mechanical acoustic vehicle alerting system

SYMBOLS		UNITS
λ	wavelength	[m]
v	velocity	[m/s]
f	frequency	[Hz]
A	amplitude	[m]
I	intensity	[W/m^2]
I_0	reference intensity	[W/m^2]
T	time period	[s]
B	Bulk modulus	[Pa]
μ	linear density	[Kg/m]
F	tension force	[N]
Y	young modulus	[Pa]
ρ	density	[Kg/m^3]
SIL	sound intensity level	[dB]
z	number of teeth	[-]
p	axial pitch	[mm]
d_a	addendum diameter	[mm]
m_x	axial module	[mm]
d	pitch diameter	[mm]
p_z	frontal pitch	[mm]

γ	pitch angle of the side curve	[º]
α_x	axial profile angle	[º]
α_n	normal profile angle	[º]
η	efficiency	[-]
f	friction coefficient	[-]

1 INTRODUCTION

Electric vehicles (EVs) have emerged as a promising solution to reduce the carbon footprint of the transportation sector. In addition to lower emissions, EVs offer a quieter and smoother driving experience than conventional internal combustion engine vehicles. However, the quietness of EVs has raised concerns about pedestrian safety, particularly in urban environments, where pedestrians may not hear the approaching vehicles. According to a study by study the National Highway Traffic Safety Administration , electric cars are involved in 37% more accidents with pedestrians than cars with internal combustion engines [1].

To address this issue, governments around the world have mandated that EVs emit warning sounds to alert pedestrians of their presence at low speeds. The United Nations Economic Commission for Europe has introduced a regulation that requires all new EVs to be equipped with an Acoustic Vehicle Alerting System (AVAS) starting from July 2019 [2]. Similarly, the National Highway Traffic Safety Administration in the United States has mandated that all new hybrid and electric vehicles must emit warning sounds at speeds up to 30 km/h by September 2020 [3].

However, the challenge is to design a noise generator that is effective in alerting pedestrians to the presence of the vehicle without compromising the energy efficiency of the vehicle. Traditional solutions, such as adding a loudspeaker or a horn, may consume a significant amount of energy, reducing the driving range of the vehicle. Therefore, researchers have explored alternative approaches that are less energy-intensive, such as using the aerodynamics or acoustics of musical instruments to create a sound generator for EVs.

This thesis aims to investigate the feasibility and effectiveness of using the principles of applied mechanics to design a noise generator for EVs that meets the regulatory requirements for pedestrian safety while minimizing the impact on the energy consumption of the vehicle. The study will evaluate various design options, such as using aeroacoustic noises, synthetic sounds, or musical notes, and assess their energy efficiency, acoustic performance, and acceptance by pedestrians.

2 SOUND AND NOISE

2.1 WHAT IS SOUND

According to definitions, sound is a particular kind of wave that moves energy through matter as a result of the material's vibrations. Pressure waves propagate through the surrounding medium or the air when an item vibrates. The energy is transferred from one particle to the next as a result of these waves making the nearby particles vibrate. The pattern of pressure changes that results from this propagates across the medium until it finally reaches our ears and allows us to hear the sound [4].

The frequency, wavelength, and amplitude of a sound wave can be used to characterize its properties. The quantity of oscillations per second, expressed in hertz, that make up a sound wave is its frequency (Hz). High frequencies correlate to noises with a high pitch, whilst low frequencies correspond to sounds with a low pitch. The distance between two successive in-phase points on a sound wave is its wavelength, whereas the greatest displacement of the particles in the medium from their equilibrium position is its amplitude. This establishes the sound's level or loudness [4].

Physicists utilise a range of instruments and methods to explore sound. Using a microphone to transform sound waves into electrical signals, which may subsequently be analysed and altered by software, is one frequent technique. Alternative methods include using an oscilloscope or spectrum analyser to measure and show the frequency and amplitude of sound waves, or utilizing ultrasound to see sound waves in real time. By researching the characteristics and behaviour of sound waves, physicists can obtain a greater knowledge of the nature of sound and its uses in domains such as medicine, engineering, and music [4].

2.2 WHAT IS NOISE

Noise is defined as an unwanted sound that interferes with communication or causes annoyance or discomfort. It is a subjective experience, with different individuals perceiving the same sound differently depending on their personal preferences, experiences, and psychological state. However, there are objective measures of noise, such as sound pressure level, frequency spectrum, and duration, that can be used to quantify its physical properties [5].

Sound pressure level (SPL) is the most commonly used metric for measuring noise, and it is expressed in decibels (dB). SPL measures the amplitude of a sound wave, which corresponds to its loudness. Sounds with high SPLs can cause hearing damage or physical discomfort, while sounds with low SPLs may not be audible or may be perceived as calming or relaxing [5].

The frequency spectrum of noise refers to the distribution of sound energy across different frequencies. The human ear is most sensitive to sounds in the range of 2,000 to 5,000 Hz, while low-frequency sounds, such as the hum of machinery or traffic noise, can be felt more than heard. Noise with a high frequency content, such as the screech of a subway train, can be particularly annoying or unpleasant, while noise with a low frequency content, such as the rumble of thunder, may be perceived as less intrusive [5].

2.3 SOUND AND NOISE

Sound and noise are two fundamental concepts in the field of physics, with significant implications for human health, communication, and well-being. According to the Physics Classroom, sound refers to any type of wave that carries energy through matter and can be perceived by the human ear. It is a ubiquitous phenomenon that can range from musical tones to environmental sounds and can be enjoyable, calming, or informative. In contrast, noise is defined as an unwanted sound that interferes with communication, causes annoyance, or discomfort. It is a subjective experience, with different individuals perceiving the same sound differently [9].

One significant difference between sound and noise lies in their subjective perception. While sound can be pleasant and desirable, noise is typically considered a nuisance. This difference in perception has significant implications for human health and well-being. Unwanted noise exposure has been linked to a range of negative health outcomes, including hearing loss, cardiovascular disease, and sleep disturbance. In contrast, exposure to pleasant sounds, such as nature sounds or music, has been shown to have beneficial effects on human health and well-being [9].

Another significant difference between sound and noise is that sound can be controlled and manipulated for various purposes, while noise reduction strategies focus on minimizing the impact of unwanted noise on human health and well-being. Physicists use a variety of tools and techniques to study sound waves and gain a better understanding of their properties and behaviour. Sound waves can be modified to create music, improve speech intelligibility, or even diagnose medical conditions. In contrast, noise reduction strategies aim to minimize the impact of unwanted noise on human health and well-being, through measures such as soundproofing, acoustic design, or noise barriers [9].

In conclusion, understanding the difference between sound and noise is crucial for developing strategies to control and manipulate sound waves for various purposes, while minimizing the impact of unwanted noise on human health and well-being. By recognizing the subjective nature of noise perception and the potential negative health effects of unwanted noise exposure, physicists, engineers, and designers can develop innovative solutions to mitigate the impact of noise on human health and well-being [9].

2.4 CHARACTERISTICS OF SOUND

2.4.1 WAVELENGTH

The wavelength of a sound wave is the distance between two consecutive points on the wave that are in phase. It is denoted by the symbol λ (lambda) and is measured in meters. The wavelength of a sound wave is related to its frequency and velocity through the formula:

$$\lambda = \frac{v}{f} \tag{1}$$

where v is the velocity of sound in the medium and f is the frequency of the wave [9].

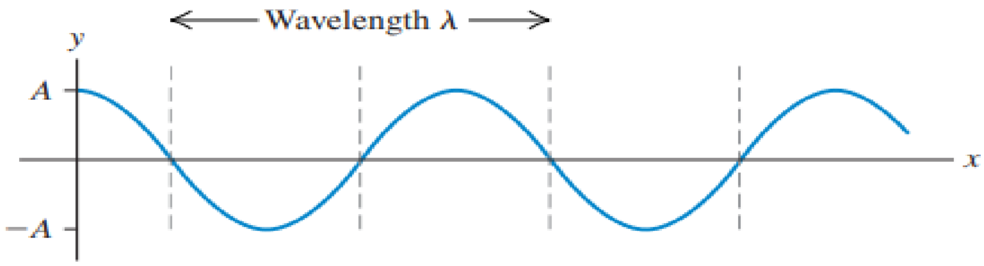

Figure 1 Wavelength illustration on a cosine wave [9].

2.4.2 AMPLITUDE:

The amplitude of a sound wave is the maximum displacement of a particle from its equilibrium position. It is denoted by the symbol A and is measured in meters. The amplitude of a sound wave is related to its intensity and is given by the formula:

$$A = \sqrt{\frac{I}{I_0}} \tag{2}$$

where I is the intensity of the sound wave and I_0 is the reference intensity, which is the threshold of human hearing $10^{-12}\,\frac{W}{m^2}$ [10].

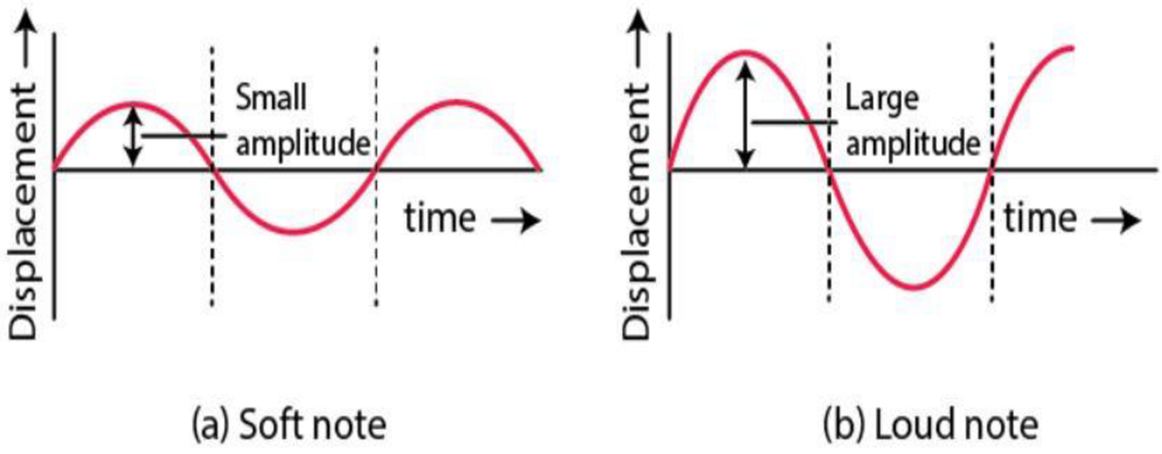

Figure 2 Difference between the amplitude of a soft note and loud note [6].

2.4.3 FREQUENCY

The frequency of a sound wave is the number of complete oscillations or cycles of the wave that occur in one second. It is denoted by the symbol f and is measured in hertz (Hz). The frequency of a sound wave is related to its wavelength and velocity through the formula:

$$f = \frac{v}{\lambda} \tag{3}$$

where v is the velocity of sound in the medium and λ is the wavelength of the wave [9].

2.4.4 TIME PERIOD

The time period of a sound wave is the time taken for one complete oscillation or cycle of the wave. It is denoted by the symbol T and is measured in seconds. The time period of a sound wave is related to its frequency through the formula:

$$T = \frac{1}{f} \tag{4}$$

where f is the frequency of the wave [9].

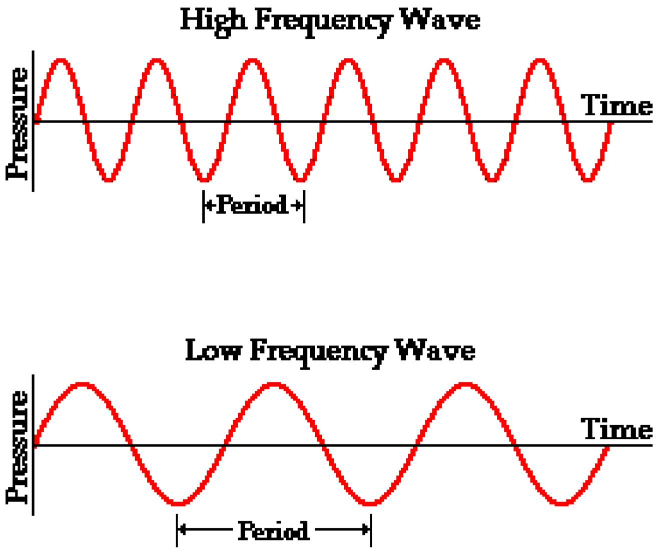

Figure 3 Period difference between high and low frequency wave [4].

2.4.5 VELOCITY

The velocity of sound is the speed at which sound waves propagate through a medium. It is denoted by the symbol v and is measured in meters per second. The velocity of sound in air at room temperature is approximately $343\ m/s$. The velocity of any wave is related to its frequency and wavelength through the formula:

$$v = f\lambda \tag{5}$$

where f is the frequency of the wave and λ is the wavelength of the wave.

The general equation for the speed of a mechanical wave v is:

$$v = \sqrt{\frac{elastic\ proprety}{inertial\ property}} \tag{6}$$

The speed of a wave on a string is:

$$v = \sqrt{\frac{F}{\mu}} \tag{7}$$

Where F is the tension in the string and μ is the linear density.

The speed of sound in a fluid depends on the bulk modulus B and density ρ:

$$v = \sqrt{\frac{B}{\rho}} \tag{8}$$

The speed of sound in a solid is:

$$v = \sqrt{\frac{Y}{\rho}} \tag{9}$$

Where Y is the young's modulus and ρ is the density [7].

Medium	**Sound Velocity (m/s)**
Air, dry (0°C and 760 mm Hg)	330
Wood (soft - along the fibre)	3400
Water (15°C)	1400
Concrete	3100
Steel	5000
Lead	1200
Glass	5500

Table 1 Speed of sound in common materials [8].

2.4.6 INTENSITY:

Sound intensity is the amount of energy that passes through a unit area per unit time. It is denoted by the symbol I and is measured in watts per square meter (W/m^2). The intensity of a sound wave is related to its amplitude and is given by the formula:

$$I = \frac{A^2 \rho v f}{2} \tag{10}$$

where A is the amplitude of the wave, ρ is the density of the medium, v is the velocity of sound in the medium, and f is the frequency of the wave.

The intensity of a sound wave can also be expressed in terms of decibels (dB), which is a logarithmic unit that compares the intensity of a sound wave to the reference intensity (I_0). The formula for the sound intensity level (SIL) in decibels is:

$$SIL = \log \frac{I}{I_0} \tag{11}$$

where I is the intensity of the sound wave and I_0 is the reference intensity [9].

2.5 SOUNDS AND HUMANS

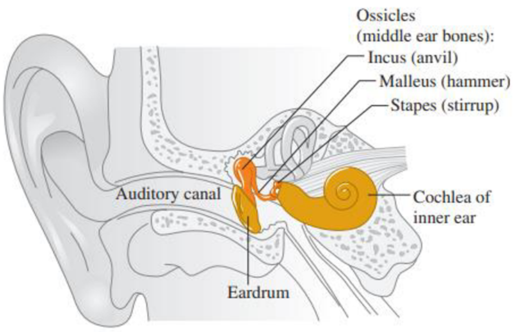

Figure 4 Human ear **Error! Reference source not found.**.

Normal sound frequencies for humans are those that fall within this audible range. Frequencies between 20 Hz and 20,000 Hz are perceived by our ears as sound and are the frequencies typically used in music, speech, and other forms of communication. For example, the fundamental frequency of a guitar string is typically between 82 Hz and 1,320 Hz, while the fundamental frequency of a male voice is typically between 85 Hz and 180 Hz, and that of a female voice is typically between 165 Hz and 255 Hz [9].

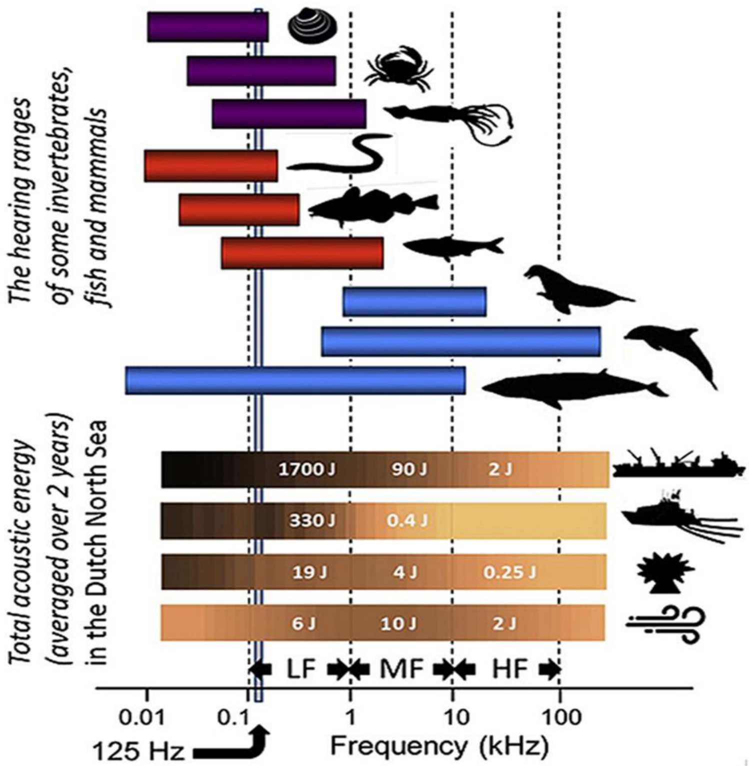

Figure 5 sound distribution [9].

In contrast, harmful sound frequencies for humans are those that fall outside the normal range of audible sound frequencies. Sound waves with frequencies above 20,000 Hz are called ultrasonic waves, while those with frequencies below 20 Hz are called infrasonic waves.

Ultrasonic waves are often used in medical imaging, industrial cleaning, and other applications, while infrasonic waves can be produced by natural phenomena such as earthquakes and volcanic eruptions [9].

However, exposure to high levels of sound in the normal audible range can also be harmful to human hearing. Prolonged exposure to sounds above 85 decibels (dB) can cause hearing damage. Sounds above 120 dB can cause immediate and permanent hearing loss. Examples of sounds that can reach these levels include rock concerts, gunfire, and jet engines [9].

In summary, normal sound frequencies for humans fall within the audible range of 20 Hz to 20,000 Hz, while harmful sound frequencies can include ultrasonic and infrasonic waves outside this range, as well as high levels of sound in the normal audible range that can cause hearing damage or loss [9].

2.6 INFRASONIC AND ULTRASONIC WAVES

Ultrasonic waves are sound waves with frequencies above the upper limit of human hearing, which is typically considered to be 20,000 Hz. Ultrasonic waves are used in many different applications, including medical imaging, cleaning, welding, and measuring. In medical imaging, ultrasonic waves are used in ultrasound machines to produce images of internal organs and tissues. The waves are directed into the body and bounce back to the machine, where they are analysed to produce images. In industrial applications, ultrasonic waves are used to clean surfaces, weld metals, and measure thicknesses of materials [9].

Infrasonic waves are sound waves with frequencies below the lower limit of human hearing, which is typically considered to be 20 Hz. Infrasonic waves are produced by a variety of natural and man-made sources, including earthquakes, volcanic eruptions, and wind turbines. Infrasonic waves can travel long distances and can be detected by animals, such as elephants and whales, that use them for communication and navigation [9].

One of the interesting aspects of ultrasonic and infrasonic waves is that they can interact with each other to produce audible sounds. For example, when ultrasonic waves are focused in a small area, they can produce a pressure wave that can be heard as a popping or cracking sound. Similarly, when infrasonic waves are produced by large sources, such as earthquakes or volcanic eruptions, they can produce audible sounds that are heard as rumbling or roaring [9].

Ultrasonic and infrasonic waves are also used in scientific research to study the properties of materials and to investigate the behaviour of animals. For example, ultrasonic waves are used to study the structure and properties of materials, such as metals and ceramics. Infrasonic waves are used to study the behaviour of animals, such as elephants, and to investigate the effects of sound on human health and well-being [9].

2.7 AGE AND HEAR LOSS

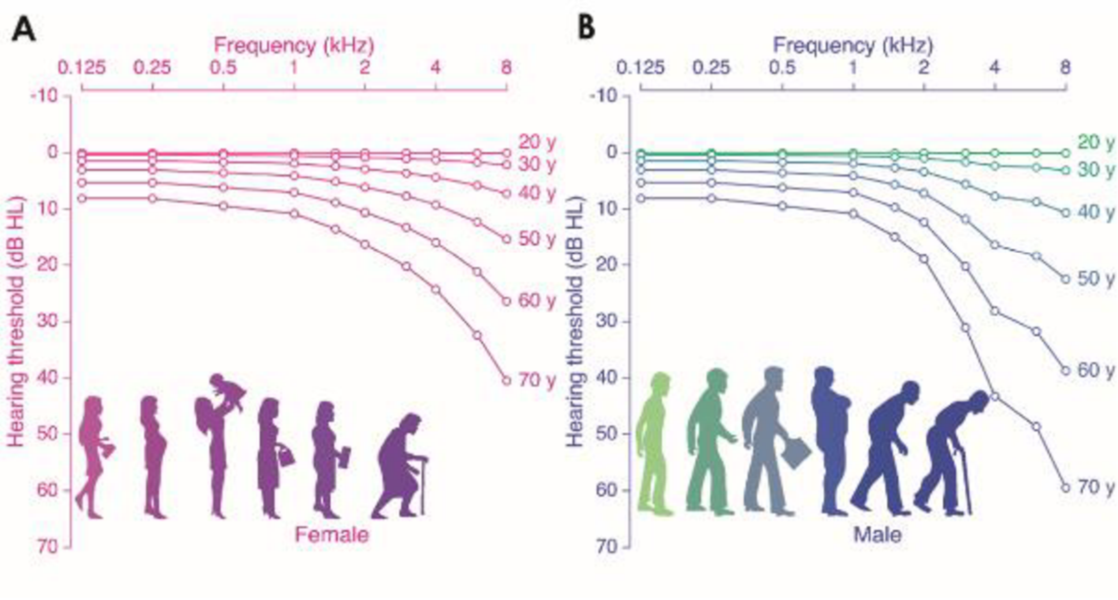

Figure 6 Age-related hearing loss according to the International Organization for Standardization (ISO) 7029 standard [11].

Age-related hearing loss, also known as presbycusis, is a common condition affecting many people as they grow older. The primary cause of this hearing loss is a gradual degeneration of the sensory hair cells in the inner ear, which are responsible for converting sound vibrations into electrical signals that are transmitted to the brain. As these hair cells become damaged or die off, the brain receives fewer signals, resulting in a reduced ability to hear sounds [1].

Research has shown that age-related hearing loss typically begins in the higher frequency ranges, such as those above 2,000 Hz, and gradually progresses to affect lower frequency sounds as well. This can result in difficulty understanding speech, particularly in noisy environments, and a reduced ability to perceive certain types of sounds, such as the high-pitched notes of a musical instrument [1].

In addition to the loss of hair cells, other changes in the ear can also contribute to age-related hearing loss. For example, the ear canal may become narrower or less flexible with age, which can affect the way sound waves are transmitted to the inner ear. Similarly, changes in the structure and function of the middle ear, such as a reduction in the flexibility of the eardrum, can also affect hearing [1].

It's worth noting that the extent and progression of age-related hearing loss can vary widely from person to person, and factors such as genetics, exposure to loud noises, and underlying medical conditions can all play a role. However, studies have shown that age-related hearing loss is a common condition affecting many people, particularly as they reach their 60s and beyond [1].

While there is no cure for age-related hearing loss, there are a range of treatments and devices that can help manage the condition and improve quality of life. These may include hearing aids, cochlear implants, or assistive listening devices, as well as lifestyle changes such as reducing exposure to loud noises and quitting smoking [1].

2.8 EFFECT OF NOISE ON HUMANS

Numerous detrimental health impacts have been connected to exposure to excessive noise. Environmental noise pollution is a serious public health issue that can lead to hearing loss, cardiovascular illness, sleep difficulties, and cognitive impairment, according to the World Health Organization [13].

According to research that was published in the journal Environmental Health Perspectives, exposure to noise levels above 60 decibels—roughly the volume of a conversation—was linked to an increased risk of heart disease, including coronary artery disease, stroke, and heart failure. The study also discovered that residents in busy streets had a higher risk of developing hypertension [13].

Noise pollution can have negative psychological impacts in addition to cardiovascular ones. According to a research that appeared in the Journal of Environmental Psychology, being around noise pollution causes higher feelings of stress, irritation, and sleep disruption. Additionally, the study discovered that anxiety and depressive symptoms were more prevalent in those who reported higher levels of noise exposure. Noise pollution may have a harmful impact on children especially. The American Academy of Paediatrics claims that exposure to loud noise can affect how children learn, behave, and develop their speech and language. According to a research in the journal Environmental Health Perspectives, children who are exposed to airplane noise have worse long-term memory and reading comprehension [13].

Human health may be significantly harmed by noise pollution, which can cause heart disease, mental health concerns, and problems with children's development. To safeguard the health and wellbeing of the general population, noise-reducing devices and construction projects like sound barriers may be required [13].

2.9 HUMAN INTERACTION WITH NOISE

Humans react to noise in different ways, ranging from irritation to physical responses. The release of stress hormones like cortisol and adrenaline can be triggered by noise exposure, according to a study that was published in the Journal of the Acoustical Society of America. The body uses this physiological reaction, sometimes referred to as the "fight or flight" response, to assist it respond to danger or stress [14].

While this reaction may be advantageous in the short term, ongoing exposure to noise can cause long-term stress, which can be harmful to one's health and well-being. Chronic noise exposure has been related to a higher risk of cardiovascular illness, disturbed sleep, and cognitive decline [14].

Humans react to noise in subjective ways in addition to physiological ways. A research in the Journal of Environmental Psychology found that people are more likely to find noise bothersome if they believe it to be unexpected or out of their control. Increased tension and unpleasant feelings like resentment and irritation might result from this impression [14].

But individual characteristics like personality and coping mechanisms can also affect how people respond to noise. People with good coping mechanisms, such meditation or mindfulness, may be better able to accept and control noise exposure. For instance, introverted people may be more sensitive to noise than extroverted ones [14].

Humans react to noise in many ways, ranging from physiological responses to feelings like displeasure. Chronic noise exposure can harm health and wellbeing, underscoring the significance of minimizing noise pollution in our settings [14].

2.10 IMPACT OF NOISE ON HUMANS

The human ear is an incredible sensory organ that plays a vital role in our daily lives. It enables us to communicate, enjoy music, and appreciate the sounds of nature. However, exposure to certain sounds can have a positive or negative impact on our hearing ability and overall health [15].

The frequency and strength of sound may be measured. The number of sound waves that travel through a certain spot in a given amount of time is referred to as frequency. Hertz (Hz) is the unit of frequency measurement. The average range of human hearing is 20 Hz to 20,000 Hz [15].

The strength or force of the sound wave is referred to as intensity, on the other hand. Decibels (dB) are the standard unit of measurement for intensity. Noise levels exceeding 85 dB can harm the inner ear and result in tinnitus or hearing loss. Gunfire and pyrotechnics, as well as other loud noises at or over 120 dB, can harm the ear both temporarily and permanently [15].

Low frequency and intensity sounds are often good sounds. Relaxing white noise, soothing music, and nature sounds like birds tweeting or a soft breeze may all help you unwind, lower your stress levels, and even drop your blood pressure. These noises are generally between 20 and 1,000 Hz in frequency and 40 and 60 dB in volume [15].

On the other hand, prolonged exposure to loud noises might be harmful to our hearing health. Loud athletic events, power tools, construction machinery, and music played at high volumes are a few frequent causes of damaging noise. It's crucial to take precautions to shield our hearing from these harmful noises. Effective techniques to protect our hearing include using earplugs or earmuffs, limiting the duration of exposure to loud noises, and lowering the level of headphones or speakers [15].

It's crucial to remember that exposure to noise can have cumulative effects. Loud noise exposure on a regular basis might eventually lead to hearing loss. Furthermore, being exposed to noise pollution may harm our physical and mental health, leading to elevated stress levels, hypertension, and cardiovascular disease [15].

The impact of noises on our hearing health is greatly influenced by their frequency and intensity. We can preserve good hearing throughout our lives by being aware of the sorts of noises we are exposed to and taking precautions to shield our ears from damaging sounds [15].

3 VEHICLE SOUND EMISSIONS REGULATIONS IN EUROPE

3.1 HISTORY

In 1970, the European Economic Community introduced its first set of regulations for vehicle noise emissions, known as Directive 70/157/EEC. These regulations set out maximum noise limits for different categories of vehicles, including passenger cars, light commercial vehicles, and heavy-duty vehicles. The maximum noise limits for each category were as follows:

Passenger cars: 74 decibels (dB) for vehicles with a maximum weight of up to 1,500 kg and 77 dB for vehicles with a maximum weight of more than 1,500 kg.

Light commercial vehicles: 78 dB for vehicles with a maximum weight of up to 1,500 kg and 81 dB for vehicles with a maximum weight of more than 1,500 kg.

Heavy-duty vehicles: 83 dB for vehicles with a maximum weight of up to 12 tonnes and 86 dB for vehicles with a maximum weight of more than 12 tonnes.

In the following years, amendments were made to these regulations. In 1987, the maximum noise limits for passenger cars and light commercial vehicles were reduced to 72 dB and 76 dB, respectively. In 1992, the maximum noise limits for heavy-duty vehicles were reduced to 80 dB and 83 dB, respectively [16].

In 1996, the EU introduced Directive 96/20/EC, which aimed to harmonize vehicle noise regulations across member states. This directive introduced a new test procedure, known as the ECE R51 test, which measured vehicle noise emissions under real-world driving conditions. The maximum noise limits for each category of vehicle were also revised, as follows:

Passenger cars: 74 dB for vehicles with a maximum weight of up to 1,305 kg and 77 dB for vehicles with a maximum weight of more than 1,305 kg.

Light commercial vehicles: 76 dB for vehicles with a maximum weight of up to 2,610 kg and 78 dB for vehicles with a maximum weight of more than 2,610 kg.

Heavy-duty vehicles: 80 dB for vehicles with a maximum weight of up to 12 tonnes and 83 dB for vehicles with a maximum weight of more than 12 tonnes [17].

Since then, there have been further amendments to the regulations. In 2014, Regulation (EU) No 540/2014 further reduced the maximum noise limits for passenger cars to 68 dB and light commercial vehicles to 71 dB [18].

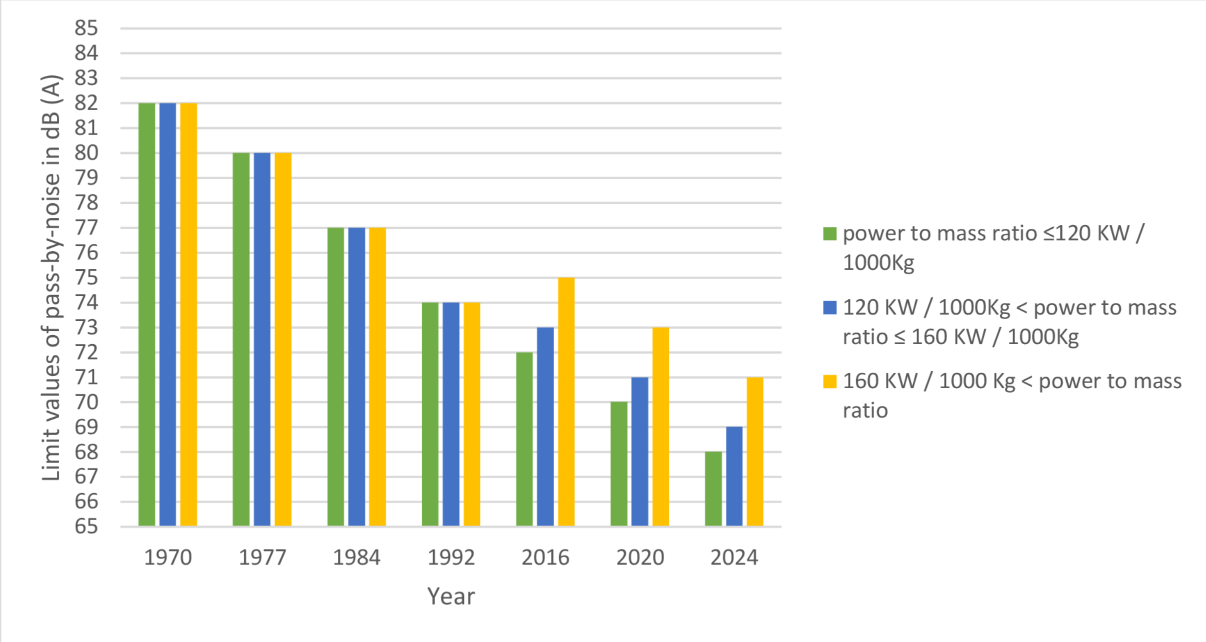

Figure 7 History of sound regulations since 1970 [19].

the history of regulations for sound emission from vehicles in Europe shows a steady trend towards tighter noise limits and more rigorous testing procedures, reflecting the increasing importance placed on reducing noise pollution and protecting public health and the environment. The regulations continue to evolve, with further changes likely in the future as governments and regulatory bodies work to minimize the impact of vehicle noise on our communities.

3.2 CURRENT REGULATIONS

In 2021, new regulations on sound emissions from motor vehicles came into effect in the European Union. The regulations apply to new vehicles and require manufacturers to ensure that their vehicles meet specific noise limits during operation (The European Parliament and Council of the European Union, 2014) [18].

For M1 vehicles, the maximum noise level is 68 decibels (dB) for petrol vehicles and 66 dB for diesel vehicles. For N1 vehicles, the maximum noise level is 74 dB for petrol vehicles and 75 dB for diesel vehicles. These limits apply to all new vehicles that are approved for sale within the European Union (The European Parliament and Council of the European Union, 2014) [18].

In addition, the regulations require new electric and hybrid vehicles to emit a warning sound when operating at low speeds to alert pedestrians and cyclists to their presence (European Parliament, 2020). The noise limit for the warning sound is set at 56 dB(A) for electric and hybrid vehicles (European Commission, 2020) [18].

To ensure compliance with the new regulations, manufacturers are required to conduct noise tests on their vehicles and provide documentation to demonstrate compliance with the regulations. The tests must be conducted in accordance with specific procedures and standards, and the results must be submitted to the relevant authorities for verification (The European Parliament and Council of the European Union, 2014) [18].

The purpose of these regulations is to reduce noise pollution and improve the quality of life for people living in urban areas. They also encourage the development of quieter and more environmentally friendly vehicles (European Commission, 2020) [18].

3.3 Methods of testing

3.3.1 Measurement of noise from moving vehicles

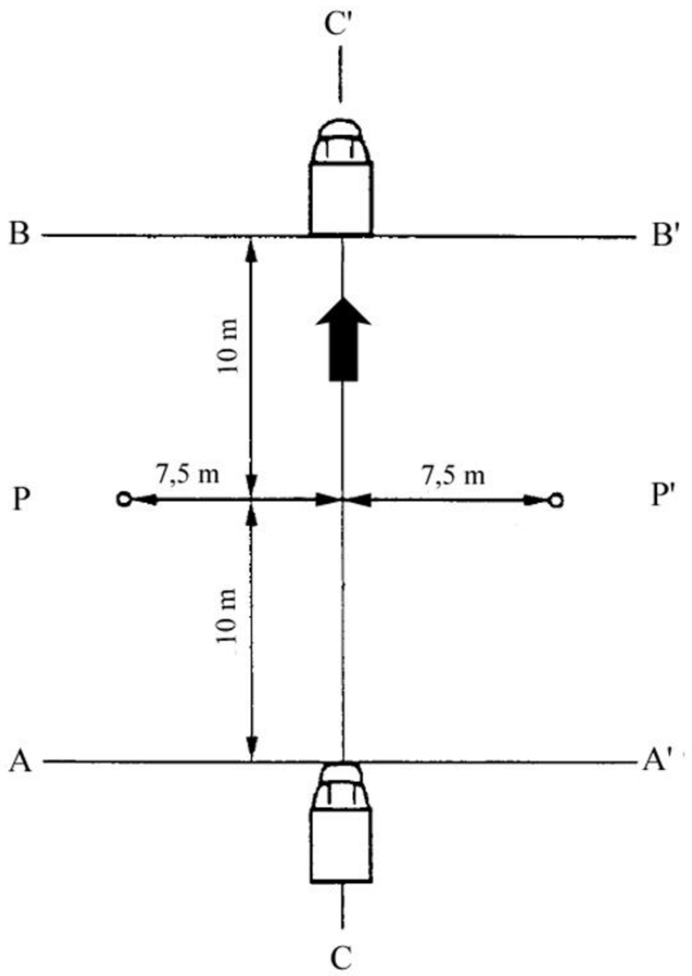

Figure 8 Measuring positions for vehicles in motion [18].

The EU regulation number 540/2014 establishes a standardized method for measuring the sound level of motor vehicles and replacement silencing systems. This method is designed to ensure that vehicles comply with the noise emission limits set out in the regulation and to reduce noise pollution caused by road traffic [18].

The measurement method specified in the regulation is based on the Worldwide Harmonized Light Vehicles Test Procedure (WLTP). The WLTP method is a global standard for measuring the emissions and fuel consumption of vehicles, and it includes provisions for measuring vehicle noise emissions [18].

The WLTP method involves placing a microphone at a distance of 7.5 meters from the vehicle while it is running on a test track. The microphone is positioned at an angle of 45 degrees to the exhaust pipe of the vehicle. The test is conducted at a constant speed of 50 km/h and under specific conditions, including ambient temperature and humidity, tire pressure, and road surface conditions, to ensure consistency and accuracy [18].

The sound level of the vehicle is measured in decibels (dB) using the "A-weighted" scale, which takes into account the sensitivity of the human ear to different frequencies of sound. The measurement is carried out at a point 1 meter from the ground and 1.2 meters from the side of the vehicle [18].

The measurement procedure is carried out in two stages. In the first stage, the vehicle is driven past the microphone at a distance of 15 meters, and the maximum sound level is recorded. This stage is called the "drive-by test." The drive-by test measures the exterior sound level of the vehicle, which includes the noise emitted by the engine, exhaust system, and tires [18].

In the second stage, the vehicle is driven past the microphone at a distance of 7.5 meters, and the sound level is measured over a period of 1 second. This stage is called the "stationary test." The stationary test measures the sound level of the vehicle at a specific point in space and time. This stage takes into consideration the noise generated by the engine, exhaust system, and tires, as well as any additional noise caused by the transmission or drivetrain of the vehicle [18].

The measured sound levels are then compared to the noise limits set out in the regulation, which vary depending on the type and weight of the vehicle. If the sound level exceeds the limit, the vehicle is considered non-compliant, and the manufacturer is required to take corrective action [18].

During the sound level test specified in the EU regulation number 540/2014, several factors are taken into consideration to ensure that the results are accurate and consistent. These factors include the test track, test conditions, test speed, test position, and sound level measurement [18].

The test track is designed to meet the requirements set out in the regulation. It should be free from any obstacles that could affect the sound level measurement, and the surface should be representative of the road conditions in the European Union. The test is carried out under specific conditions, including ambient temperature and humidity, tire pressure, and road surface conditions, to ensure consistency and accuracy. These conditions are standardized to ensure that the test results are comparable across different vehicles and test facilities [18].

The test is conducted at a constant speed of 50 km/h. This speed is chosen because it is representative of the average speed of vehicles in urban areas and ensures that the sound level measurement is carried out under realistic driving conditions. The microphone used to measure the sound level of the vehicle is positioned at a specific distance and angle from the exhaust pipe of the vehicle. This ensures that the sound level measurement is taken from a consistent and representative position [18].

4 CAR MANUFACTURES AND NOISE GENERATION

4.1 NOISE AND PEDESTRIAN SAFETY

Vehicle noise is an essential safety feature for pedestrians, particularly for visually impaired individuals who rely heavily on sound cues to navigate the streets safely. Vehicle noise can provide pedestrians with a warning of a vehicle's presence, movement, and speed, allowing them to adjust their movement accordingly to avoid collisions.

Without adequate car noise, pedestrians may not be able to detect the presence of a vehicle, and this can lead to dangerous situations. For example, a pedestrian may step out into the road without realizing that a car is approaching, or they may not be able to judge the distance or speed of an oncoming vehicle accurately.

Electric vehicles (EVs) and hybrid vehicles, which produce less noise than traditional gasoline vehicles, pose a unique safety risk to pedestrians. The quietness of these vehicles makes it more difficult for pedestrians to detect them, particularly in urban areas with a lot of ambient noise. This can be particularly dangerous for visually impaired pedestrians, who may not be able to detect the presence of a vehicle, misjudge its distance, or perceive its speed.

To address this safety concern, the European Union has enacted regulations requiring EVs and hybrid vehicles to produce a minimum level of sound when traveling at low speeds. The regulation, known as the EU Regulation 540/2014, requires that all new electric and hybrid vehicles must be fitted with an Acoustic Vehicle Alerting System (AVAS) that emits an artificial sound when the vehicle is traveling at speeds below 20 km/h (12 mph). The AVAS system must be activated whenever the vehicle is in an urban environment, such as in a city or town [18].

In summary, vehicle noise is crucial for pedestrian safety, particularly for visually impaired pedestrians. Regulations such as the EU Regulation 540/2014 highlight the importance of developing new solutions to ensure pedestrian safety while also addressing the environmental benefits of electric and hybrid vehicles.

4.2 DIFFERENT SOLUTIONS FOR PEDESTRIAN ALARMING SYSTEMS

4.2.1 VOLKSWAGEN AND RENAULT-NISSAN-MITSUBISHI ALLIANCE

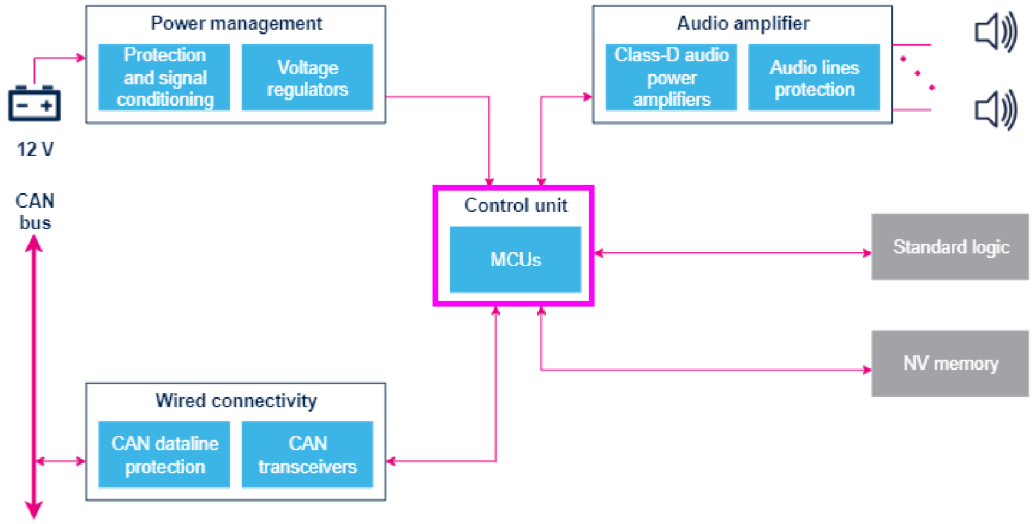

Figure 9 AVAS system scheme [20].

The Acoustic Vehicle Alerting System (AVAS) is an audible warning system used on electric and hybrid vehicles to alert pedestrians and cyclists of their presence at low speeds. The system is designed to mitigate the risk of pedestrian accidents, particularly for the visually impaired or those who may not be able to hear an electric vehicle approaching due to the lack of engine noise. The AVAS system emits a sound that is similar to a traditional gasoline engine, allowing pedestrians to recognize the presence of a moving vehicle.

Figure 10 The compact AVAS pedestrian warning system [21].

Volkswagen and Renault-Nissan-Mitsubishi Alliance are two major automakers that use an AVAS system. Volkswagen's AVAS system is standard on its electric vehicles, including the e-Golf and ID.3, and uses speakers mounted in the front and rear of the vehicle to emit the sound. The system adjusts the sound according to the vehicle's speed and is designed to be audible to pedestrians without being intrusive to the vehicle's occupants.

Similarly, the Renault-Nissan-Mitsubishi Alliance uses an AVAS system that is designed to emit a sound when the vehicle is traveling at speeds up to 30 km/h (19 mph). The sound is intended to be audible to pedestrians and cyclists, but not to be intrusive to the vehicle's occupants. The AVAS system uses speakers mounted on the exterior of the vehicle to emit the sound and adjusts according to the vehicle's speed.

The specific sound emitted by AVAS systems can vary between automakers and models but is generally designed to be distinctive and easily recognizable as a moving vehicle. Some AVAS systems emit a sound that is similar to a traditional gasoline engine, while others may use a more futuristic or sci-fi inspired sound.

AVAS systems have become a requirement for electric vehicles in many countries, including the United States, the European Union, and Japan. The regulations specify that electric vehicles must emit a warning sound when traveling at speeds up to 30 km/h (19 mph) to alert pedestrians and cyclists of their presence. The introduction of AVAS systems has helped to improve pedestrian safety and reduce the risk of accidents involving electric vehicles [22][23].

4.2.2 Tesla

Tesla's solution to the noise limit for pedestrian safety is to use external speakers that emit a low-level humming noise when the vehicle is traveling at low speeds. This sound is designed to alert pedestrians to the presence of the vehicle and help prevent accidents. Tesla's sound system is customizable, and owners can choose from a range of different sounds, including a futuristic sci-fi sound or a traditional gasoline engine sound. The volume of the sound adjusts according to the vehicle's speed, and the sound system can also be turned off by the driver if necessary. Tesla's approach has been praised for its creativity and effectiveness in ensuring pedestrian safety [23].

4.2.3 General Motors

General Motors' solution to the noise limit for pedestrian safety is a sound system called "Pedestrian-Friendly Alert," which emits a low-pitched sound when its EVs are traveling at speeds below 30 km/h. The sound is designed to be audible to pedestrians but not to be intrusive to the vehicle's occupants. The system uses front and rear speakers to emit the sound, which adjusts according to the vehicle's speed. The sound is designed to be distinctive and recognizable, with General Motors conducting extensive research to determine the most effective sound for pedestrian safety [25].

4.2.4 Ford

Ford's solution to the noise limit for pedestrian safety is a sound system called "Quiet Flight," which emits a sound that is similar to a spaceship or aircraft. The sound is designed to be distinctive and easily recognizable, helping pedestrians to identify the presence and direction of the vehicle. The sound system uses front and rear speakers to emit the sound, which adjusts according to the vehicle's speed. Ford has worked with sound designers to create a unique and engaging sound for its EVs, with the "Quiet Flight" sound designed to evoke a sense of futuristic technology [26].

5 PROPOSED MODELS

5.1 MUSIC BOX NOISE GENERATOR

5.1.1 MODEL IDEA

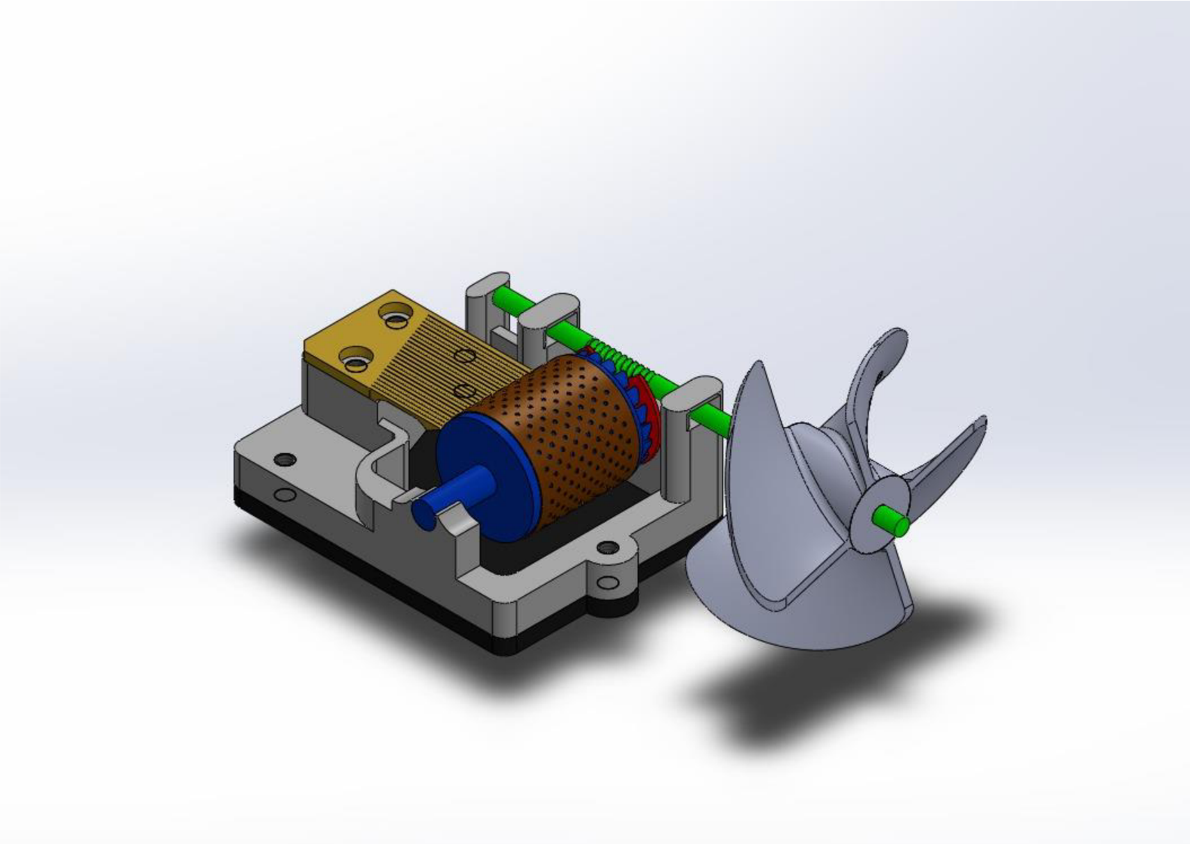

Figure 11 Music box Noise generator.

The model proposed in this thesis is based on the concept of utilizing a music box to generate noise. This novel approach was inspired by the field of aerodynamics, where the air flow generated by wind blowing against a moving vehicle can be harnessed as a driving force for a fan. The fan would then transfer its energy through a shaft to the music box, causing an increase in frequency as the relative velocity between the car and the wind increased. The proposed model aims to build upon this concept by exploring the potential of using a similar mechanism to generate noise in a controlled manner. By integrating the music box noise generator with an electronic control system, the frequency and amplitude of the noise produced can be modulated according to specific parameters such as vehicle speed, engine RPM, and external conditions. This model has significant implications for the fields of transportation and acoustics, as it offers a new approach to reducing energy consumption and noise pollution associated with traditional sound production methods.

5.1.2 Model Operation

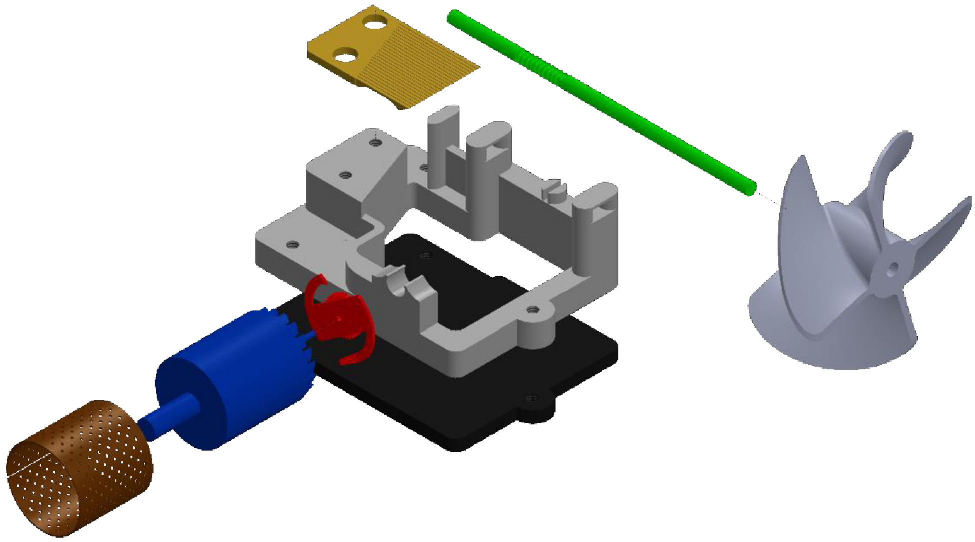

Figure 12 Detailed view of the model.

Base	Worm	Shaft	Shield
Drum	Worm wheel	Comb	Fan

Table 2 Model parts.

The concept behind this model revolves around utilizing the power of wind as a source of energy. Positioned under the hood in the front of the engine bay near the car radiator, the device harnesses the incoming air to initiate its operation. As the wind enters, it sets the fan in motion, which in turn rotates the shaft and the worm mechanism. This rotational motion drives the drum connected to the system. The drum is equipped with a sheet that features several pins strategically placed along its surface. As the drum spins, these pins interact with the lamellas of the comb, causing them to vibrate and generate a distinct sound. The unique arrangement of pins and lamellas allows for the creation of specific sound patterns as the device operates. This innovative mechanism not only relies on renewable wind energy but also adds an auditory dimension to electric vehicles, enhancing safety for pedestrians and other road users by providing an audible cue of the car's presence. The design of this noise generator prioritizes efficiency and effectiveness, ensuring that the produced sound remains within acceptable levels and does not disrupt the overall driving experience. By utilizing the power of wind and the vibration of pins and lamellas, this ingenious device contributes to the growing development of environmentally friendly transportation while addressing the concern of electric vehicle noise in a creative and efficient manner.

5.1.3 WORM GEAR EFFICIENCY CALCULATION

Gear parameters:

according to [27] the gear efficiency is calculated by the following way:

The worm is single thread so $z = 1$

Axial pitch: $p_x = 0.91mm$

Addendum diameter: $d_a = 2.5mm$

Gear axial module: $m_x = \frac{p_x}{\pi} = 0.3mm$ (12)

Pitch diameter: $d = d_a - 2m = 1.92mm$ (13)

Frontal pitch: $p_{z=}p_x * z = 0.91mm$ (14)

Pitch angle of the side curve: $\tan\gamma = \frac{p_z}{\pi * d} = 0.15 \rightarrow \gamma = \tan^{-1}(0.15) = 8.58°$ (15)

Axial profile angle: $\alpha_x = 20°$

Normal profile angle: $\tan\alpha_n = \tan\alpha_x * \cos\gamma = 0.36 \rightarrow \alpha_n = 19.79°$ (16)

Gear efficiency equation: $\eta = \frac{\cos\alpha_n - f\tan\gamma}{\cos\alpha_n + f\cot\gamma}$ (17)

The geometry, load, speed, surface polish, material combination utilized in mating gears, environmental factors, and wear characteristics all have a significant role in friction and wear characteristics. For plastic on steel, the coefficient of friction normally ranges from 0.10 to 0.40, while for plastic on plastic, it ranges from 0.12 to 0.60 [28].

Friction coefficient range: $f_1 = 0.12$

$f_2 = 0.6$

Efficiency range: $\eta_1 = 53.1\%$ for $f_1 = 0.12$

$\eta_2 = 17.3\%$ for $f_2 = 0.6$

5.2 MAVAS (MECHANICAL ACOUSTIC VEHICLE ALERTING SYSTEM)

5.2.1 MODEL CONCEPT

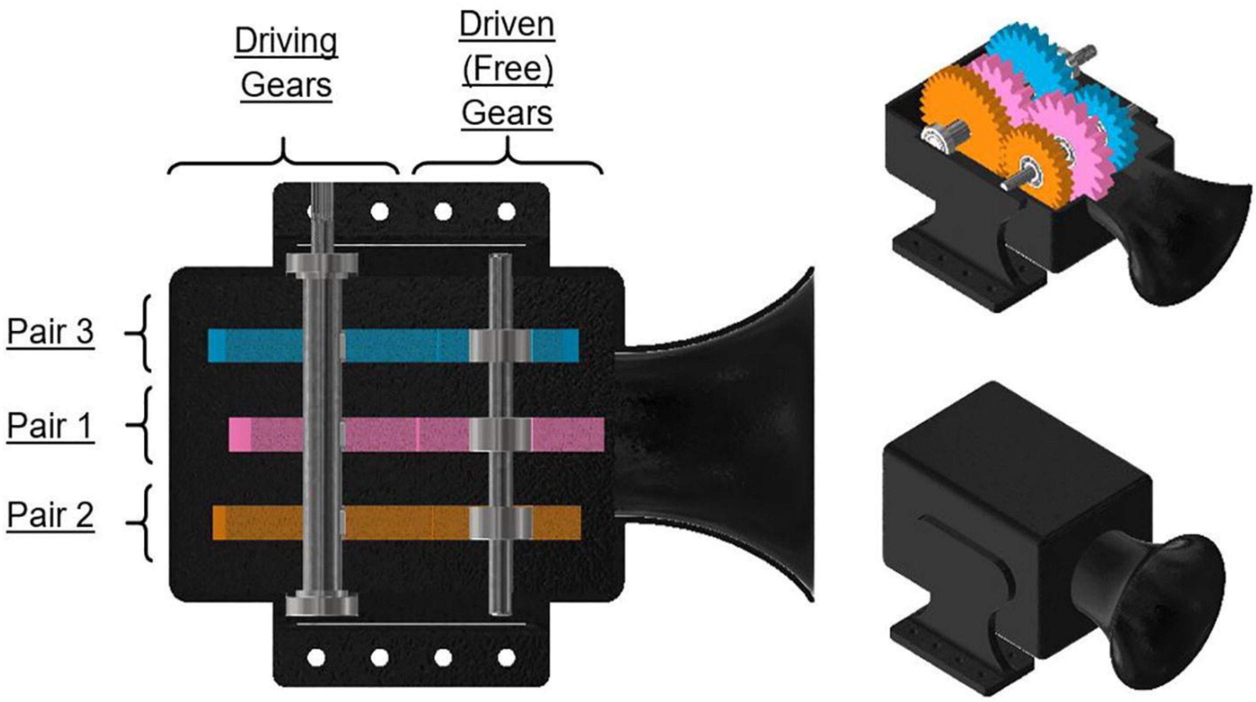

Figure 13 Mechanical Acoustic Vehicle Alerting System [29].

The MAVAS is an innovative device designed to address the need for noise generation in electric vehicles, particularly at low speeds between 0 and 20 km/h. As the world shifts towards greener transportation solutions, electric vehicles have become increasingly popular. However, their quiet operation poses a potential safety concern for pedestrians who may not hear the approaching vehicles, especially in urban environments where low-speed manoeuvring is common [29].

The MAVAS model aims to solve this problem by utilizing a gearbox integrated within a sound amplification case. The gearbox consists of three sets of gears, each with different modules with a thickness of 16mm, strategically designed to generate noise when the electric vehicle is moving at low speeds. The gears, crucial components of the system, are specifically constructed from steel due to its durability and strength [29].

Gear Pair	Module [mm]	Driving wheel teeth	Driven wheel teeth
1	5	17	19
2	3	35	25
3	4	27	18

Table 3 Gear Pairs module and number of teeth [29].

The design of the MAVAS gearbox incorporates driven shafts with bearings, allowing them to rotate freely. This feature ensures smooth operation and reduces friction, enabling the gears to efficiently transmit power from the electric engine. Notably, the gearbox does not require lubrication, simplifying maintenance requirements [29].

By converting the rotational motion of the electric engine into audible noise, the MAVAS system effectively alerts pedestrians of an approaching electric vehicle when it is operating at speeds between 0 and 20 km/h. The sound amplification case further enhances the generated noise, ensuring it reaches an appropriate volume level for sufficient pedestrian awareness [29].

The MAVAS model represents a significant advancement in pedestrian safety for electric vehicles. By combining mechanical engineering principles, acoustic amplification, and careful gear design, it offers an effective solution to mitigate the potential risks associated with the reduced noise emissions of electric vehicles, particularly when they are operating at low speeds in urban environments [29].

5.2.2 Design and Functionality of the MAVAS

The MAVAS (Mechanical Acoustic Pedestrian Alerting System) model incorporates a unique gearbox arrangement to generate noise as an electric vehicle moves at low speeds between 0 and 20 km/h. Powered by an electric engine, the gearbox plays a crucial role in converting rotational motion into audible sound, ensuring the safety of pedestrians during low-speed manoeuvres [29].

The gearbox consists of three sets of gears, each with different modules, made from robust steel materials for durability. These gears are integrated into the driven shafts, which are equipped with bearings. The bearings allow the shafts to rotate freely, minimizing friction and enabling smooth transmission of power from the electric engine to the gears [29].

As the electric engine rotates, it transfers its rotational energy to the first set of gears within the gearbox. The gear configuration is carefully designed to amplify the mechanical noise produced during this transmission. The rotation continues to the subsequent gear sets, each with its specific module, further enhancing the generated noise [29].

To maximize the effectiveness of noise generation, the MAVAS model incorporates a sound amplification case. This case is strategically designed to amplify and project the generated noise, ensuring it reaches an audible level for pedestrians in the vicinity. The combination of the gearbox's noise-generating capabilities and the sound amplification case guarantees an effective alerting system for pedestrians [29].

The MAVAS model is specifically engineered to operate when the electric vehicle is moving at low speeds between 0 and 20 km/h. This targeted speed range ensures that pedestrians are alerted during urban driving conditions and other situations where low-speed manoeuvring is required. By generating audible noise in this speed range, the MAVAS system provides a clear and effective warning to pedestrians, enhancing their safety and awareness [29].

5.3 MODEL COMPARISON

The music box model is wind powered and relatively light since it will be 3d printed from plastic material so the model will not affect the car on the level of power usage or car weight, but the design contains a worm gear and worm gears come with a low efficiency, and the wind idea comes with a disadvantage that the model would need to be placed in a very specific way to work and it may not function at low speeds so testing is required.

On the other hand, the MAVAS model somehow heavy since it is made of steel and it is powered by an electric engine so this may affect the car lowering the car range per full charge, but this model may have a better noise quality and it can give the driver the experience of a combustion engine noise which is produced by the contact of the gears.

CONCLUSION

The advent of electric vehicles (EVs) presents a hopeful prospect for diminishing the carbon footprint attributed to the transportation industry. The increase of electric vehicles is posing a threat to pedestrians and cyclists on the streets due to the low noise emissions from these types of vehicles.

In the aim to address this issue, first we started by studying the general concept of noise and sound where we represented the sound characteristics, the effect of noises on humans and the human interaction with sounds.

Second, we provided the noise emissions legislations, we started with the legislation in Europe in the 1970's followed by the years 1984, 1996 till the present regulation (EU) No 540/2014. From these regulations we realised that the sound emissions from vehicles is decreasing from 82 dB in 1970 to 71 dB in 2024 this shows the aim of Europe to reduce the noise pollution and these regulations vary between different type of vehicles depending on the vehicle mass and engine type such as diesel and petrol, and in 2014 regulations were introduced to put a noise minimum for electric and hybrid vehicles to minimize the danger to pedestrians.

Third, a research was done about the solutions done by car manufacturers to solve the quietness issue in electric vehicles, most of the companies had the same approach using a system called acoustic vehicle alerting system which is a noise generator that is electric powered and produce noise at lower speeds (30 km/h), the sound is usually emitted by speakers or audio devices.

In the last chapter of the thesis, a model proposal was introduced which is a music box that is wind powered by a fan and it is mounted in the front of the car in a wat that the fan will harness the wind energy and turn it into torque moment that powers this model. The music box contains a worm gear that we calculated the efficiency for it which was between 17.3% and 53.1% for a friction coefficient for plastic parts in contact since the model will be 3d printed. This efficiency is relatively low, so the proposed solution for it is to use a more efficient gear pair such as straight spur gears that are famous for their high efficiency and low maintenance. A second was introduced which was developed by Miguel Rodriguez which is basically a gear box made of 3 sets of steel straight spur gears inside a sound amplifier case, in his work it is stated that the gear box will be powered by a small electric engine.

Finally, the music box model needs more calculations and testing to know the best position of the model, if the fan will produce enough torque to make it function properly and the noise quality that will be produced. This thesis can be used as background for a future work.

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