The Effectiveness of Alert Sounds for Electric Vehicles Based on Pedestrians' Perception

Ferran Mocholí Belenguer, Antonio Martínez-Millana, Francisco Sales Castells Ramón, and Antonio Mocholí-Salcedo

***Abstract*— One of the largest problems with electric vehicles is that they often go unnoticed by pedestrians due to the absence of noticeable noise generated by electric motors, which is a potential cause of accidents and collisions. Surprisingly, this positive property in terms of reducing the noise pollution is in fact becoming a road safety problem. In addition, with the promotion of electric traction vehicles due to new environmental policies and the current proliferation of personal mobility vehicles, this problem could even be increased in the coming years. Therefore, the future global road regulation has included aspects on noise and warning sounds that electric vehicles must emit in the years to come. However, despite the requirements, no specific signal type or many other features have been established. Only the emission levels have been set (56-75 dB). Consequently, within the framework of this problem, this article evaluates the acoustic characteristics of the sound that should be emitted by electric vehicles so that pedestrians can easily detect them and the optimal sound pressure level they should emit to not unnecessarily raise noise pollution levels, concluding that the emission limits established are excessive in certain scenarios and that optimal warning sounds must be focused on electronically imitating combustion engine noises.**

***Index Terms*— Accidents, acoustics, electric vehicles, noise, pedestrians, polution, safety, traffic, warning sounds.**

I. Introduction

The transportation sector is constantly changing and evolving due to the increasingly internal and global integration of technologies, and it is currently attempting to achieve intelligent and collaborative transportation with less pollution [1]. However, with the continued growth in the world population, a further increase in the vehicle fleet is expected in the coming years, which will soon result in unsustainable traffic within major cities if no action is taken [2]. The imminent consequences of this growth will be closely related to a loss in productivity, as well as increases in accidents and pollution and their corresponding negative impacts on public health. Therefore, to minimize all these effects, increase road safety and protect the environment, traffic management and control with Intelligent Transportation Systems has emerged as a current worldwide priority [3].

All of the above implies a continuous installation and improvement of the current road infrastructure, which is redefining itself today. A few years ago, this infrastructure was merely limited to physical components, such as barriers, traffic lights and signals. However, the future road infrastructure will be forced to include new components, sensors and intelligent systems to adapt to the current technological changes [4]. In addition, since roads cover a large proportion of the land area, especially within cities, an ideal future to expect would be that a large number of emerging technologies could turn this currently passive element into a slightly more productive element.

This change is the main reason why it is increasingly common to hear about Smart Cities [5]. This term refers to urban development based on sustainability, which is taking place in major world capitals due to the new urban policies focused on social investments, improvements in the energy and transportation infrastructure, the development of new communication technologies and many other actions that contemplate and promote quality of life without interfering with sustainable economic-environmental development.

The technological changes caused by the emergence of mobile applications and new technologies are also causing an unexpected effect on the urban mobility of major cities, which has completely changed the typical mode of transportation. These new technologies, which are applied to the automotive industry, big data and the shared economy, are changing the way in which the population approaches the world of transportation. In fact, in recent years, we have seen a massive and revolutionary proliferation of personal mobility electric vehicles in the major world capitals, which have forced several regulations and policies to be quickly drafted to control and manage their use efficiently [6].

However, although new legislation has now been developed to encourage the transformation of conventional cities into Smart Green Cities, in which the number of combustion vehicles is gradually reduced, there is currently a serious safety problem with electric vehicles due to their lack of sonority [7]. This problem is the reason why the US National Traffic

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Ferran Mocholí Belenguer is with the Traffic Control Systems Group, ITACA Institute, Universitat Politècnica de València, 46022 Valencia, Spain. (e-mail: fermocbe@gmail.com).

Antonio Martínez-Millana is with the SABIEN Group, ITACA Institute, Universitat Politècnica de València, 46022 Valencia, Spain.

Francisco Sales Castells Ramón and Antonio Mocholí-Salcedo are with the Department of Electronic Engineering, ITACA Institute, Universitat Politècnica de València, 46022 Valencia, Spain.

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Fig. 1. Dangerous road situations.

Safety Administration and the European Union have demanded that, from 2020 and 2021, respectively, vehicles must include warning systems to warn pedestrians of their presence, which is aimed at reducing accidents due to this cause [8], [9]. However, despite this requirement, no specific type of signal or many other features have been specified; that is, creative freedom has been offered under certain premises, resulting in each automobile company independently developing its own technology and sonority.

One of the main benefits of electric and hybrid vehicles compared to combustion vehicles is precisely that they generate no noise. This fact was indeed thought to pleasantly help in the reduction of urban noise pollution in cities [10], but paradoxically, their greatest virtue has become an inconvenience for the safety of other users. The reality shows that these vehicles, which have become part of the urban vehicle fleet and circulate daily with other users and means of transportation, are causing many situations, such as those in Fig. 1, in which this coexistence poses a potential road safety hazard.

In fact, it has been proven that these types of vehicles are involved in more traffic accidents than conventional combustion cars used to be involved in [11], which has specifically affected pedestrian safety.

Fig. 2 shows the number of drivers and pedestrians killed in traffic accidents in recent years in Spain [12], in which it can be seen that as the number of killed drivers has declined drastically, while the number of pedestrians killed in traffic accidents has not followed this same trend. Although this figure dropped considerably over time, in recent years, it has increased, precisely by the rise in accidents caused by electric vehicles. Comparing the data of the last two years for both scenarios, it can be observed that the number of drivers killed in traffic accidents has been reduced by 2,25% but that the number of killed pedestrians has increased by 11%, which is an alarming figure.

Thus, it is evident that the lack of sound produced by these vehicles is becoming a serious road safety problem that requires intelligent systems for a solution. In addition, apart from the previous figures, which focus on Spain, there are many other recent studies around the world that also corroborate these data. Some of the most significant are:

- ➢ Electric cars are up to 35% more likely to run over a pedestrian than cars with conventional motors. This figure rises to 57% with respect to the likelihood of an accident with a cyclist. These are the conclusions of a study prepared by the National Highway Traffic Safety Administration of the United States (NHTSA) [13].

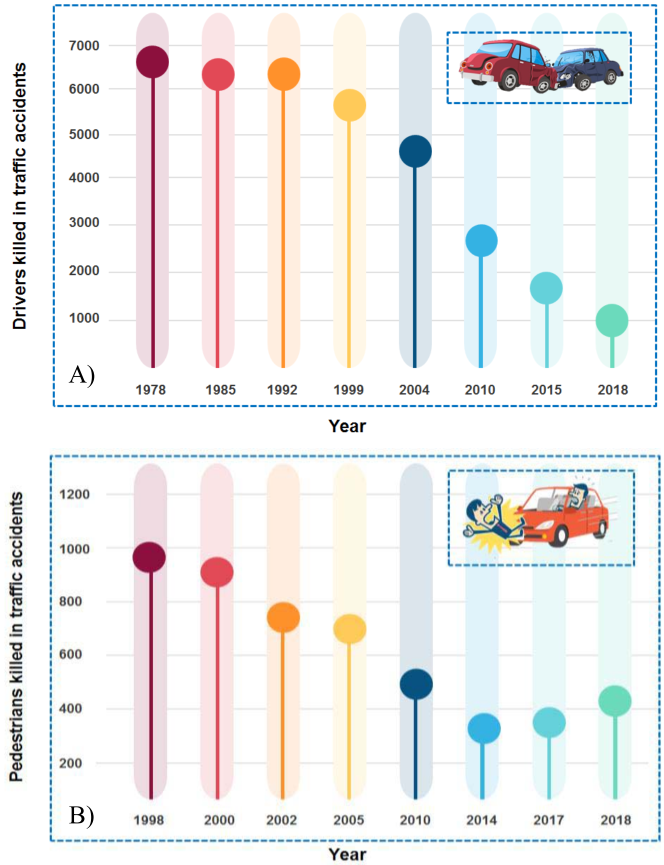

Fig. 2. Number of (a) drivers and (b) pedestrians killed in traffic accidents.

- ➢ Personal mobility vehicles cause approximately one accident per day, but this figure is expected to triple by next year. These are the conclusions of a study prepared by the Línea Directa Foundation [14].
- ➢ Electric and hybrid vehicles need to be 74% closer than a combustion-engine car for pedestrians to hear them and react properly to avoid accidents. These are the conclusions of a study prepared by The University of California [15].
- ➢ Powerful, high-end electric cars are 40% more likely to suffer an accident than an equivalent combustion vehicle. These are the conclusions of a report prepared by the French insurance company AXA based on its claims data [16].

Consequently, in view of this serious problem of road safety that society faces today, the motivation involved in conducting this study is justified by the following facts:

- ➢ The recent regulations developed by the European Union and the American National Highway Traffic Safety Administration on the obligation of alert systems in electric vehicles.
- ➢ The preventive and corrective environmental measures to combat pollution and reduce climate change that are being taken by major cities and countries.
- ➢ The increasingly unanimous decision of developed countries to accelerate the introduction of electric vehicles through different types of incentives.

- The rapid proliferation of personal mobility electric vehicles produced in recent years.
- The current problems related to the accident rates of electric vehicles and their coexistence with other vehicles.
- The obligation of automobile manufacturers to obtain low emissions in the overall calculation of their vehicles (they need to incorporate nonpolluting vehicles into their fleet).
- Continuous restrictions on certain areas of cities where only the use of electric vehicles or ECO and ZERO certifications are allowed.

II. Materials and Methods

A. Obligations of Warning Systems

As of July 1, 2019, a new measure by the European Union entered into force that obligates vehicles to follow minimum sound emission requirements so that they can be more easily perceived by pedestrians. From now on it will be necessary to equip new hybrid and electric vehicles with an AVAS (Acoustic Vehicle Alerting Systems) acoustic alert system.

It is intended that this community law applies to newly approved cars from July 1, but from July 2021, it will be extended to all commercialized models. In this way, this measure aims to give manufacturers and consumers an adaptation time. This modification is directed, as indicated by the institution itself, to category N and M vehicles; that is, vehicles destined for the transportation of people and goods, but it is expected that this will also be applied to personal mobility vehicles in the next few years. Some municipalities indeed have already begun to force some personal mobility vehicles to be secured precisely because of the continuing problems they are causing.

Accordingly, electric and hybrid vehicles will be forced to emit sounds when they circulate at less than 20 kilometers per hour and in reverse; at a higher speed it is understood that aerodynamic noise and noise from the tires will be sufficient. However, the sound emitted can be individually designed by the different manufacturers, since the European Union law has only specified that, as a recommendation, it should be similar to that of a traditional combustion engine. The only aspect that the European Commission has set is the range in which the emission level must be, in this case, between 56 and 75 dB. In addition, they have indicated that the manual deactivation of this system will be completely prohibited, an option that was possible in some advanced models before this reform.

B. Sound Characterization

Noise and environmental pollution are two of the main problems facing the urban areas of major metropolises. However, despite the measures promoted by sustainable mobility promotion policies, the reality is that many areas of these urban centers are currently acoustically saturated due to the high volume of traffic.

The noise emitted by a car is essentially composed of three factors: the noise emitted by the engine, the noise produced by the contact of the wheels with the asphalt and the noise produced by the wind cut. Nevertheless, the dominant noise source mainly depends on the speed. Whereas at low velocities the engine noise dominates –which is only applicable to combustion vehicles–, the noise of the tires and wind turbulence becomes progressively dominant as the speed increases [17]. Nonetheless, the speed at which those noise sources get over engine noise also depends on the engine, tires, asphalt properties and aerodynamic design.

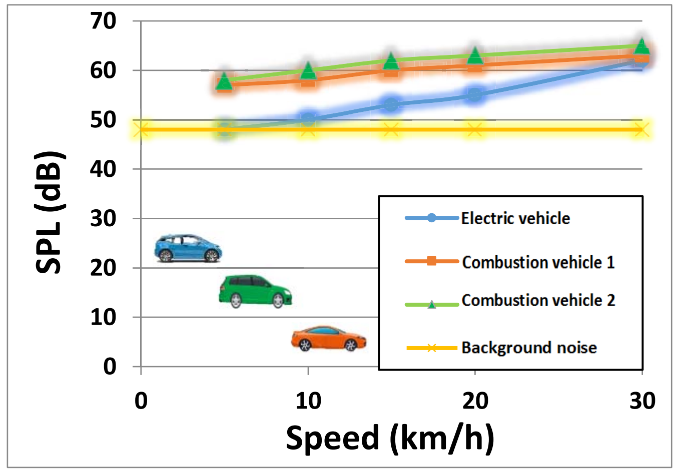

Fig. 3. Comparison of SPL in combustion and electric vehicles.

The most frequent situation in urban environments is the starting of vehicles when they are stopped at traffic lights. In these scenarios, the engine noise is remarkably predominating, radiating low-frequency energy that generally cannot be absorbed by nearby building elements. These low frequency components radiated by the combustion engine are related to their type and speed, and easily enter into homes, causing discomfort in the daily lives of citizens. In addition, at street level low frequency components make verbal communication difficult.

The electric motor offers a number of interesting advantages in the face of the above problems; it is much quieter, has a much more balanced operation, has no vibrations, has a higher performance and does not emit gases. In addition, its maintenance is practically nil compared to that of a combustion engine. However, as seen, their problem is that they are too quiet in urban traffic. At reduced speeds, which are the most common at urban intersections, only tires radiate noise, and generally, electric vehicles usually have a slightly lower tire section than combustion vehicles, further decreasing their sound contribution.

Consequently, Fig. 3 shows the results of a study comparing the noise emitted by combustion vehicles and electric vehicles for speeds from 0 to 30 km/h. The test was conducted in the afternoon in the parking lot of the 'Polytechnic City of Innovation' of the Universidad Politécnica de Valencia with three different vehicles. This place was chosen since the Traffic Control Systems Research Group has a location there with magnetic loops and thus a cabin with electrical access. The background noise of the stage during the measurement was 49 dB and the measurements were made with a Brüel & Kjær 2250L sound level meter.

It is thus observed that, at low speeds, the difference between a combustion vehicle and an electric one can be quite

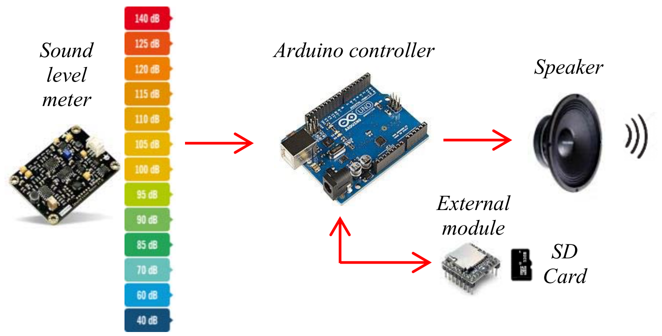

Fig. 4. Components and operation diagram of the proposed system.

significant (approximately 10 dB). Above 20 and 30 km/h, the noise produced by the tires causes the differences to become less pronounced, which is why the European Union has demanded warning systems for speeds just below 20 km/h. Moreover, it should also be noted that in environments with greater ambient noise, which are very common in the main roads of cities, the sound produced by electric cars is completely masked by background noise, practically independent of its speed.

C. Proposed System

The objective of this research is to analyze what type of alert sound is optimal to guarantee the complete safety of pedestrians and if the limits established by the European Union are adequate in all possible urban settings. With this idea, we set out to design and implement the system shown in Fig. 4 that was able to monitor the background noise, emit alert sounds through a speaker and then compare both levels. Thus, the objective to be achieved is to prove if with these emission levels, vehicles emit the minimum level of acoustic pressure necessary for pedestrians to hear them easily but without generating unnecessary noise pollution. In this way, this study essentially aims that these new alert systems are adaptive and thus emit noise based on the environmental conditions; it does not make sense to emit with the same intensity at noon when the urban noise is high than at night when it is minimum.

For this reason, using a combination of several technologies and devices is proposed. This will entail an Arduino controller, the capture of the background noise level by means of an Arduino compatible sound level meter, the emission of different sounds previously stored in an SD card by a speaker and subsequent data processing.

D. Sound Level Meter Specifications

For the system to be developed, the SEN0232 Gravity sound level meter from the company DFRobot was chosen, which is compatible with an Arduino. This sensor is capable of accurately measuring the signal level of the environment through a low noise microphone. In addition, it is a seamless Plug-and-Play technology, which simplified and further facilitated its implementation in our application.

The technical specifications of this device are [18]:

➢ Measuring range: 30 dBA ∼ 130 dBA.
➢ Measurement error: ± 1.5 dB.

TABLE I
FEATURES OF THE CHOSEN LOUDSPEAKER

Parameter	Minimum	Value	Maximum
Size	-	77mm	-
Impedance	6,8 Ω	8 Ω	9,2 Ω
Resonance	192 Hz	240 Hz	288 Hz
SPL	87 dB	90 dB	93 dB
Frequency range	192 Hz	-	7000 Hz
Rated power	-	1 W	2W

➢ Frequency response: 31.5 Hz ∼ 8.5 kHz.
➢ Input voltage: 3.3 ∼ 5.0 V.
➢ Input current: 22 mA - 3.3 V, 14 mA - 5.0 V.
➢ Output voltage: 0.6 ∼ 2.6 V.
➢ Module size: 60 mm x 43 mm.

In this sensor the circuitry is designed in such a way that the decibel value is linear with the output voltage; that is, when the output voltage is 0.6 V, the sound pressure level will be 30 dBA, while when the output voltage is 2.6 V, this value will be 130 dBA. The calibration of this relationship is performed in the factory on a prototype, which was an extra reason to opt for this product. Therefore, through this signal sensor we obtain the following relationship:

$$Value in decibels\,(dBA) = Output voltage(V) \times 50 \quad (1)$$

In addition, it must be taken into account that the measured dBA decibels filter the low frequencies in order to be more representative, since the human being has less sensitivity to low frequencies than to medium and high ones.

E. Emission Specifications

In addition to analyzing whether the limits established by the European Union are adequate in all possible urban scenarios, in our research, different warning signals will also be used to check which is more effective and thus have a first impression of user preferences. This test will lead us to reproduce three different types of signals that will have different durations and characteristics, but above all different spectral contents. For this reason and in view of the utility and the scenario in which our system will be used, we will need a speaker that:

➢ Is able to emit fairly throughout the frequency range.
➢ Is able to emit at a high power.
➢ Is small.
➢ Is omnidirectional.

With the previous premises, GA0776 speaker from the manufacturer CUI Global was finally chosen, whose most important specifications are detailed in Table I. As can be seen, the speaker can emit sounds up to 93 dB (SPL), which far exceeds the upper emission limit set by the European Union.

F. Reproduction Specifications

To play any MP3 or WAV sound with an Arduino, an external module with an SD card that connects to it is required. The external module chosen was the DFPlayer Mini from the DFRobot company.

This equipment is a small audio player module that consists of a slot for micro SD cards that can be controlled by a

TABLE II
FUNCTION OF THE DFPLAYER MINI PUSHBUTTONS

Push button	Function
1	Next alert sound
2	Pause
3	Volume up
4	Volume down

microcontroller, which in this case is an Arduino. Some of the most notable features of this are the following:

- ➢ It has a built-in amplifier that can manage speakers up to 3 W in stereo or mono, which can achieve a maximum sound pressure level of 90 dB SPL.
- ➢ It has a 24-bit analog to digital converter.
- ➢ It supports MP3 and WAV decoding.
- ➢ It has 6 different equalizer levels and 30 levels of volume adjustment control.

In addition, to give it a greater flexibility, since it was intended to perform tests in real urban environments, the system was provided with a 7-segment display and several push buttons to perform different functions, which are detailed in Table II.

G. Operating Mode

The next step was to program a function in Arduino capable of constantly monitoring the background noise, emitting signals through the speaker, obtaining the difference between levels and showing it on the display. Consequently, the operation of the system is as follows:

- ➢ Arduino monitors the background noise level by taking 5000 measurements and averaging them. This value is taken as $SPL_{BACKGROUNDNOISE}$.
- ➢ Next, the Arduino sends the order to play sounds through the speaker via the external SD module. These sounds can be modified using the buttons described above. These signals have been purposely modified so that their dynamic range is minimized and thus provide a continuous pressure level.
- ➢ The SPL_{TOTAL} is calculated by summing the reference level $SPL_{BACKGROUNDNOISE}$ with the level measured by the sound level meter while the speaker is emitting. This level, therefore, consists of the contribution of the speaker $SPL_{SPEAKER}$, for which 5000 measurements are also taken and averaged, and the contribution of the background noise $SPL_{BACKGROUNDNOISE}$.

$$SPL_{TOTAL} = 10\log\left(10^{\frac{SPL_{BACKGROUND\ NOISE}}{10}} + 10^{\frac{SPL_{SPEAKER}}{10}}\right) \quad (2)$$

- ➢ Then, the Arduino performs the following mathematical operations to obtain, on one hand, the real SPL level at which the speaker emits ($SPL_{SPEAKER}$), and on the other hand, the sound pressure level above the background noise that this causes (ΔSPL). This last value is the one that is displayed on the 7 segments.

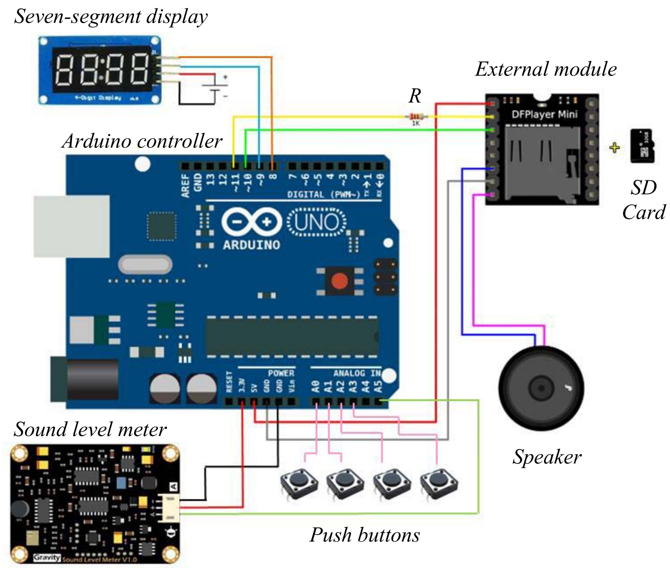

Fig. 5. System connection.

$$SPL_{SPEAKER} = 10\log\left(10^{\frac{SPL_{TOTAL}}{10}} - 10^{\frac{SPL_{BACKGROUND\ NOISE}}{10}}\right) \quad (3)$$

$$\Delta SPL = SPL_{TOTAL} - SPL_{BACKGROUND\ NOISE} \quad (4)$$

In this way, the Arduino will start the process again for each measurement, thus remonitoring the level, calculating the difference and sending it to the display in real time.

Then, once it was known how our system works and the components it was composed of, the next step was to interconnect all the components and check the code for Arduino, available in 'ArduinoCode', which execute all the previously described tasks. Fig. 5 shows a schematic of how the different elements were configured.

However, there was an added issue to solve before it could be terminated; that is, there is a problem with a loudspeaker operating in free space, which is that the rear wave interacts with the front wave, thereby cancelling out low and medium frequencies. In addition, since our speaker has a small size, these would be canceled even at higher frequencies. Therefore, they are normally placed in boxes. Thus, we had to sufficiently screen the rear wave with a wooden box. However, this fact would not be an added problem in cars, since the same vehicle chassis could even act as a screen. Consequently, we placed the speaker in a dimensions $22 \times 12 \times 9$ mm box as seen in Fig. 6. In this way:

- ➢ We took advantage of this space to put the remaining components and cables in a fixed and orderly manner.
- ➢ Due to its portable nature, the Arduino USB power supply was replaced with a 9 V battery.
- ➢ The sound pressure level was placed 1 meter away in a straight line with respect to the speaker cone.
- ➢ The 7-segment display was incorporated into the case housing.

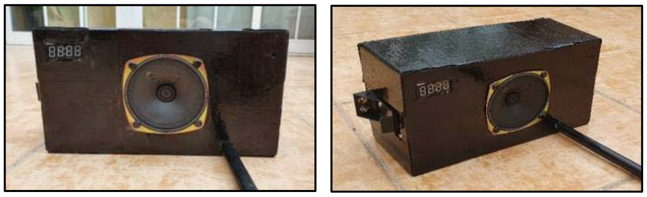

Fig. 6. Final design of the implemented system.

TABLE III

EQUIVALENCE BETWEEN ANSWERS AND MEANINGS

Response	Detectability	Satisfaction
0	Impossible to detect	Tremendously unpleasant
1	Very difficult to detect	Very unpleasant
2	Hard to detect	Unpleasant
3	Moderately detectable	Nice
4	Detectable	Very nice
5	Fully detectable	Tremendously pleasant

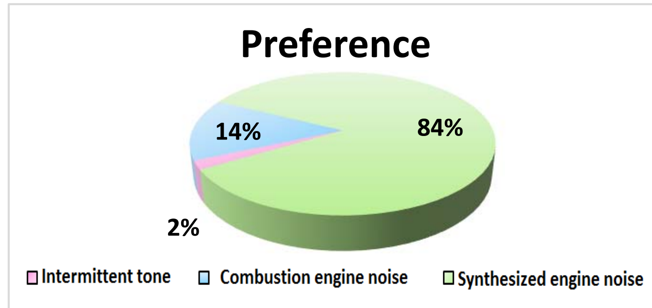

Fig. 7. Preference.

III. RESULTS

A. Alert Sounds

Sounds are part of our daily life. There are sounds that displease us, sounds that entertain us, sounds that excite us and sounds that stress us. Even silence can stimulate us. All these sounds influence us in the course of the day, but not all of them do so in the same way. Thus, although the physical principle is the same, the reactions and sensations that they produce can be quite varied.

Consequently, our research, in addition to analyzing whether the limits established by the European Union are adequate in all possible scenarios, will also attempt to determine what type of sound would be most suitable for this purpose. Thus, a series of psychoacoustic tests were performed to explore what kind of sounds are more pleasant, and therefore, more appropriate for this system. In this way, three different sounds were used and a series of subjective tests were performed by using the implemented system. These sounds, available in 'WarningSounds', precisely attempted to reproduce the three most elementary sensations that music can cause: pleasure, discomfort and attention. These were:

- ➢ Intermittent tone: the sound produced by traffic lights adapted for blind people at intersections was taken as a reference. It tried to cause attention.
- ➢ Combustion engine noise: the typical sound produced by the engines of combustion vehicles was taken as a reference. It tried to cause discomfort.
- ➢ Synthesized engine noise: the sound of the 'Canto' alert system that some Nissan vehicle models have already implemented was taken as a reference. It tried to cause pleasure.

Consequently, three tests using the system implemented and the signals described above were conducted on a sample of 50 people ranged in age from 18 to 26 years on 'Avenida de los Naranjos', a typically congested street near the surroundings of the Polytechnic University of Valencia. It was decided to perform the tests to those people and in that scenario and not at laboratory level precisely because they were intended to be as similar as possible to scenarios that we will find in a few years on our roads and young participants with good hearing abilities were sought. The templates used and whose equivalence between answers and meanings are available in 'TestTemplate' and Table III. They basically intended to figure out:

- ➢ The degree of detectability of these warning sounds.
- ➢ The level of satisfaction of each warning sound.
- ➢ The preference towards them.

The methodology followed was very simple:

- ➢ Participants between 18 and 26 years old were sought along Avenida de los Naranjos. It was verified by means of the national identity document.
- ➢ If participants were interested in taking the test, they were given a simplified version of the pure tone audiometry test (using headphones).
- ➢ If the audiometry result was normal hearing between -10 dB and -20 dB, the participant was selected. Those participants who showed a slight hearing loss were discarded.
- ➢ What the test was going to consist of was detailed. In this way, participants knew what kind of sounds they were going to hear. However, they had not previously heard them.
- ➢ Next, participants were given the answer sheet. They took a few minutes to read it and to check that they understood how to respond.
- ➢ The participants were placed at 8 meters in a straight line from the speaker piston. This is the distance that the European Commission has calculated as 'safe' for the pedestrian to be able to realize that an electric vehicle is approaching and react if necessary [9].
- ➢ The three signals were independently emitted for 45 seconds, varying in intensity from less to more. The order was: first, the intermittent tone, second, the combustion engine noise, and third, the synthesized engine noise.
- ➢ After each sound, the participants were asked to indicate the level of satisfaction and the degree of detectability experienced with these sounds.
- ➢ Finally, once they had heard all the warning signals, participants were asked to determine what the most pleasant sound had been.

The results of these tests are shown in Figs. 7-9.

B. Emission Level

European regulations have delimited the emission limits between a margin ranging from 56 dB to 75 dB, but it is

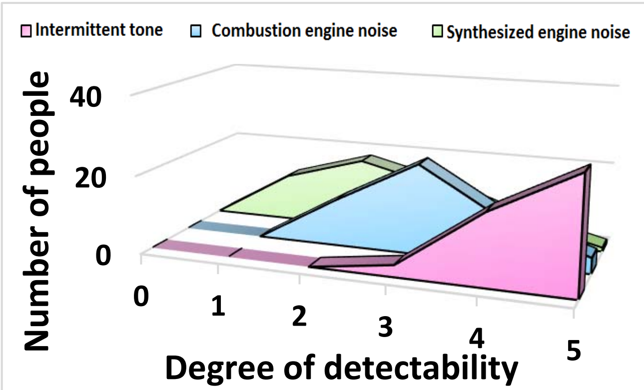

Fig. 8. Degree of detectability.

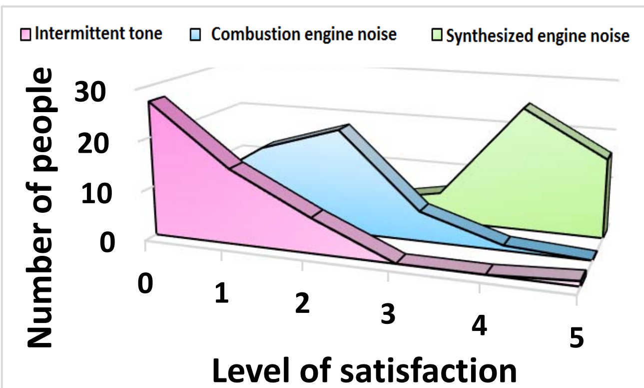

Fig. 9. Level of satisfaction.

evident that this system must be adaptive. It should not emit with the same intensity on a silent stage as on a highly noisy stage. For this reason, by means of a methodology similar to the previous tests, this point addresses the elaboration, realization and verification of different tests to analyze whether the limits established by the European Union are adequate in all possible urban scenarios.

As the European Union has recommended that warning sounds should artificially imitate the sound of a combustion engine and vary with speed, which is consistent with the preference that our study has determined (84%) and the sounds that car companies are currently developing, the sound used to perform these tests was precisely the synthesized engine noise.

In our study, $SPL_{BACKGROUNDNOISE}$ is defined as any noise from nature and various human activities, including transportation. Consequently, SPL_{TOTAL} will be calculated as the superposition of two sources: the background noise ($SPL_{BACKGROUNDNOISE}$) and the noise generated exclusively by the warning signal ($SPL_{SPEKAER}$). Then, taking the previous consideration and the fact that our system shows precisely the difference in the level achieved regarding the background noise (ΔSPL), a series of essays were conducted in real environments so that they could be related to the different scenarios shown in Table IV.

The peculiarities of the study are detailed below:

- The same tests were performed in five different environments to contrast silent, quiet, normal, noisy and very noisy data according to Table IV. For this purpose, background noise was first monitored in different scenarios and with these values, the best locations were chosen to carry out the essays.
- The five scenarios selected are shown in Table V:
- Fifty people participated in each test in the diurnal environments. In the night environments, due to the scarce traffic of personnel, only 20 people took part in each test.
- Participants ranged in age from 18 to 26 years. This was done on purpose as young participants with good hearing abilities were sought.
- As in the previous test, those participants interested in taking the test underwent rapid audiometry. If its result was normal hearing (between -10 dB and -20 dB), the participant was selected. Otherwise, they were discarded.

In this way, each trial consisted of four steps:

1) After explaining the test, each participant was again placed at a distance of 8 meters in a straight line with respect to the loudspeaker. The reason for this distance has been previously explained [9].
2) The system implemented was initialized. Consequently, the background noise was monitored and then the warning signal (synthesized engine noise) was emitted with the minimum possible level.
3) The Arduino obtained ΔSPL and displayed its value on the 7 segments.

TABLE IV
SCENARIOS IN WHICH THE TESTS WERE INTENDED TO BE CARRIED OUT

Ambient	SPL	Possible scenario
Silent	< 40 dB	Secondary streets at dawn
Quiet	40 dB – 50 dB	Main streets at dawn
Normal	50 dB – 60 dB	Fluid secondary streets at noon
Noisy	60 dB – 70 dB	Main streets fluid at noon
Very noisy	70 dB – 80 dB	Congested main streets

TABLE V
REAL SCENARIOS IN WHICH THE TESTS WERE CONDUCTED

Ambient	SPL	Scenario	Day/Time (Measure)
Silent	33,8 dB	Carrer del Músic Chapí	08/19/2019 – 22:30
Quiet	45,5 dB	Calle del Gravador Jordán	08/19/2019 – 23:30
Normal	51,9 dB	Carretera Zorilla	08/19/2019 – 16:00
Noisy	63,3 dB	Avenida de los Naranjos	08/20/2019 – 11:00
Very noisy	71 dB	Avenida Ausiàs March	08/20/2019 – 13:00

All the previous streets are in the city of Valencia. (Zip Codes 46013 and 46022).

Fig. 10. Picture taken while testing in Avenida de los Naranjos.

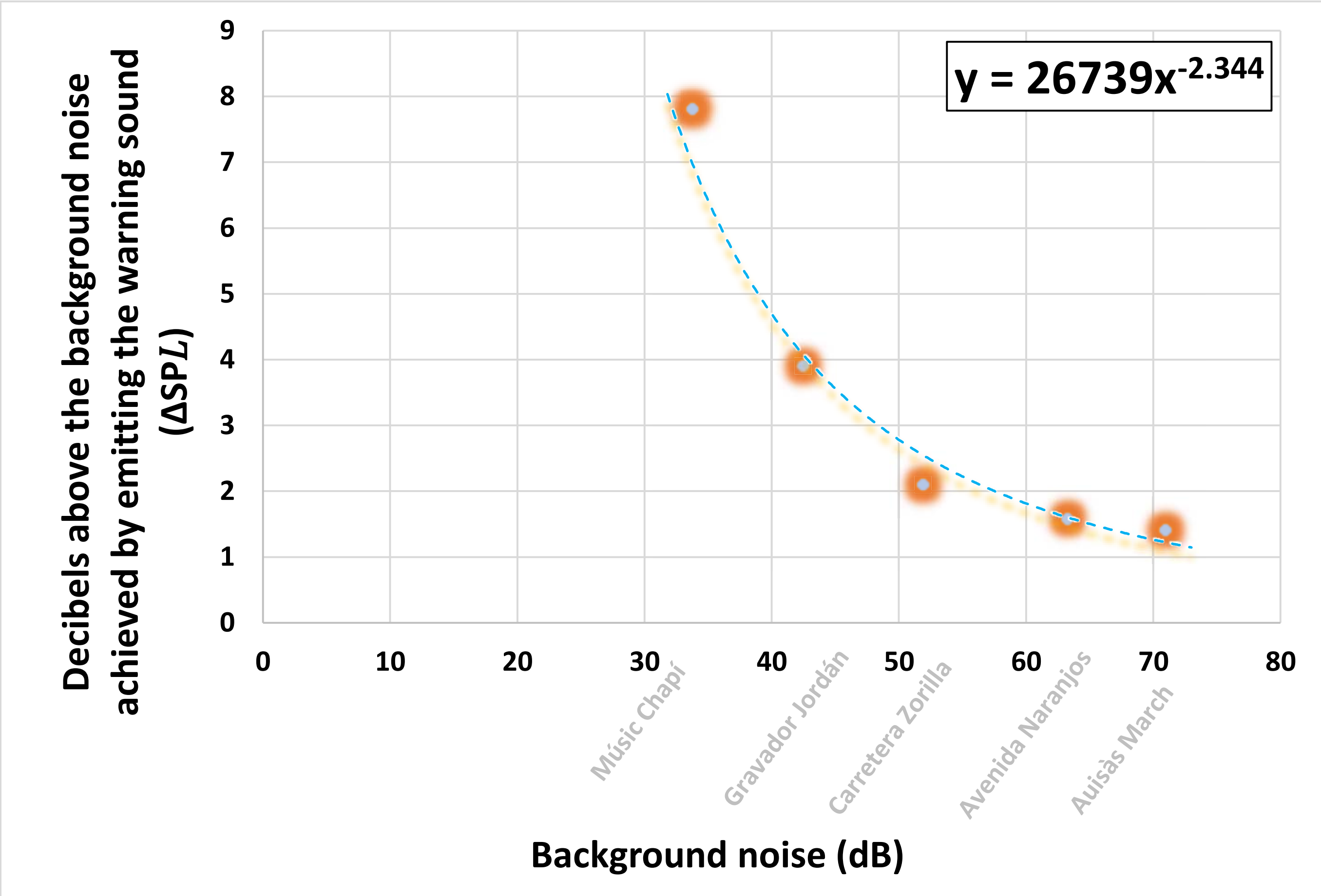

Fig. 11. Decibels above the background noise achieved when emitting the warning sound.

TABLE VI
Δ SPL OBTAINED IN THE DIFFERENT SCENARIOS

Ambient	Scenario	SPL	ΔSPL
Silent	Carrer del Músic Chapí	33,8 dB	7,8 dB
Quiet	Calle del Gravador Jordán	45,5 dB	3,9 dB
Normal	Carretera Zorilla	51,9 dB	2,1 dB
Noisy	Avenida de los Naranjos	63,3 dB	1,58 dB
Very noisy	Avenida Ausiàs March	71 dB	1,40 dB

TABLE VII
NUMERICAL RESULTS OF THE PILOT FIELD TRIALS

Ambient	ΔSPL	SPLBACKGROUND NOISE	SPLSPEAKER	S^2
Silent	7,8 dB	33,8 dB	40,81 dB	1,22
Quiet	3,9 dB	45,5dB	44,12 dB	0,69
Normal	2,1 dB	51,9 dB	49, 83 dB	0,62
Noisy	1,58 dB	63,3 dB	59,78 dB	0,41
Very noisy	1,40 dB	71 dB	66,80 dB	0,24

4) The participant was asked if they were possible to hear and distinguish the alert sound clearly between the background noise. If the answer was yes, this value was scored and thus the test was terminated. If the answer was no, the level of emission was increased to the next possible level and the test was performed again until an affirmative answer was obtained. Fig. 10 is shown for clarification.

The numerical results of these tests are shown in Table VI, which shows the sound pressure level above the background noise averaged in each scenario (ΔSPL).

Keeping in mind Equations 2, 3 and 4, from Table VI several conclusions can be drawn:

- ➢ When the background noise is low, a minimal speaker contribution raises considerably SPL_{TOTAL}.
- ➢ When the background noise is high, a higher emission intensity is required to alter SPL_{TOTAL}.
- ➢ Decibels above the background noise achieved when emitting the warning sound (ΔSPL) decrease rapidly according to the same background noise increases.

These above values have been shown graphically in Fig. 11 with an additionally regression line added. However, for a better understanding, from this data, Table VII and Fig. 12 have also been added, in which the corresponding emission level that the speaker should emit ($SPL_{SPEAKER}$) depending on background noise ($SPL_{BACKGROUNDNOISE}$) is shown. In addition, variance (S^2) values have also been added. For this, taking Equations 2 and 4 into account, the following relationship has been applied:

$$SPL_{SPEAKER} = 10\log\left(10^{\frac{SPL_{BACKGROUND\ NOISE}+\Delta SPL}{10}} - 10^{\frac{SPL_{BACKGROUNDNOISE}}{10}}\right) \quad (5)$$

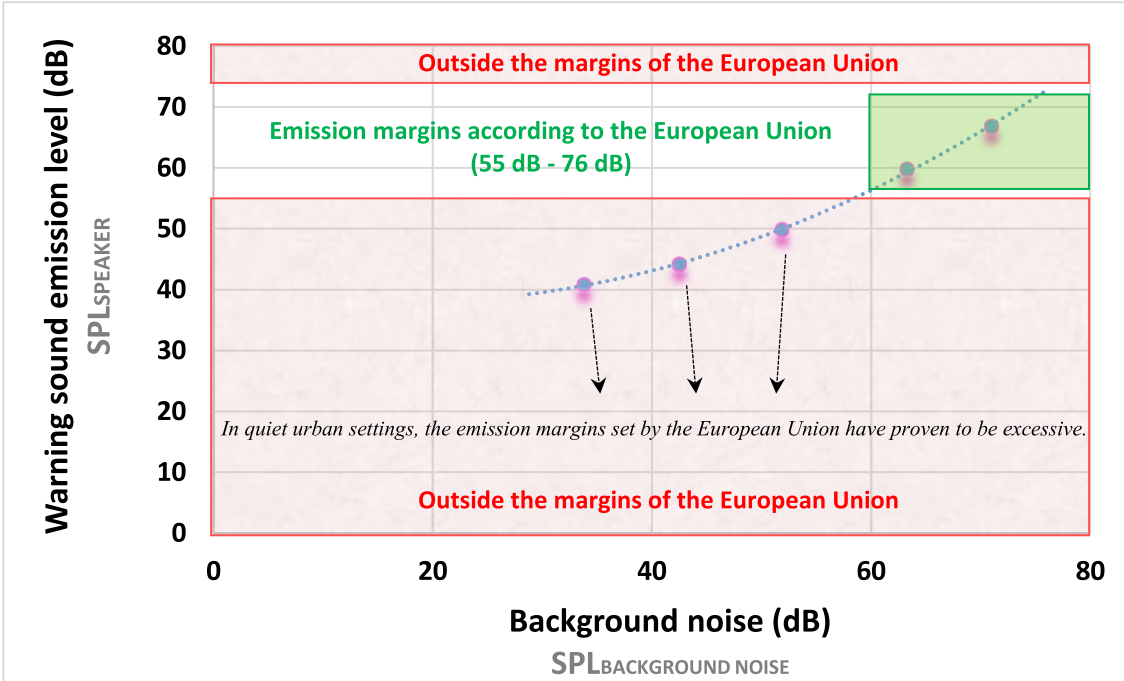

Fig. 12. Warning sound emission level.

IV. Conclusion

Electric and hybrid vehicles, as well as different personal mobility vehicles, are considered to be the future of transportation in smart cities and the key to the total reduction of noise and pollution in urban areas. However, to guarantee road safety for all users, several problems associated with this type of vehicle must be addressed beforehand, since the use of this type of vehicle has recently shown an increased risk in urban environments due to the presence of a tremendously silent transportation system. The main problem is their noise levels, since they are indeed much different from their predecessors, which we are all accustomed to. Consequently, various city councils, committees and traffic-related organizations are currently trying to analyze the problem and look for feasible solutions. However, the most significant measure so far has been the use of acoustic warning systems in vehicles, which will be fully effective in approximately one year. Hence the importance of this study.

This recent decision has been encouraged because this lack of noise has proven to be a serious problem in the road safety of pedestrians and cyclists, especially for the most vulnerable groups, such as children, the elderly or blind people. This absence of noise has proven to result in a drastic decrease in the detectability of the vehicle, which has caused a considerably increase in accidents and collisions in recent years in major world cities.

In accordance with the recommendations of the informal work group Quiet Road Transport Vehicles (QRTV) of the United Nations, the warning sounds should meet certain requirements from the point of view of road safety and the environment:

- ➢ They should be easily audible and localizable.
- ➢ Its directivity should be such that it can be properly determined by pedestrians regardless of their position.
- ➢ They should be socially acceptable.
- ➢ They should not increase the acoustic contamination of cities or excessively alter the sound landscape.

Our psychoacoustic tests on the level of satisfaction, preference and degree of detectability have confirmed that the optimal signals should focus mostly on being mere imitations of the engine noise of a combustion car (but produced artificially by music software). It seems to be the route that most of the car companies are taking, which fully coincides with the European Union recommendation and the result of our study (84% preference). Notwithstanding this, our study (84% preference). Notwithstanding this, that fact that the most detectable sound, the intermittent tone, is the most unpleasant is extremely curious as well as confusing, since it presents a challenge to work on. Due to the very nature of our ear and brain and the way in which they respond to different stimuli, it was obvious that an intermittently reproduced attention sound made up of few frequency components would be easier to detect, but our research showed that detectable sounds should not be used at the expense of being unpleasant, since the noise pollution they would generate would be unbearable. The results of our tests do demonstrate this. Thus, the imminent future work to be done before the final implantation of the AVAS system should focus on developing a sound that, in addition to being acoustically pleasing and electronically imitating a combustion car engine, is more detectable.

On the other hand, the emission margins proposed by the European Commission (56-75 dB) have not proved to be the most suitable for this new system. A first conclusion of this research is that emission levels of alert sounds can be in general reduced with respect to those margins. On the other hand, they should be adaptive to the background noise level, which would be especially beneficial in quite environments. Nevertheless, it is worth mentioning that these psychoacoustic tests were carried out with young and healthy people. In order to confirm these conclusions, further research with a larger population including aged subjects (therefore affected by presbycusis) as well as subjects with hearing impairments should be carried out, as they may also interact in real scenarios.

In addition, it should be noted that with the future expansion of electric vehicles, urban sound landscapes are expected to have a reduced amount of noise, which would cause the optimum emission levels to be still lower. In Fig. 12, it can be seen that only under certain circumstances the established European limits would be adequate. In quiet scenarios these margins have been shown to be greater than necessary.

Finally, we would like to highlight that this research is not about setting new emission limits. It is not intended that the results shown in Fig. 12 become the new limits to which vehicles should emit in the future. This study was designed to find an appropriate balance for the level of the alert sound to be detectable whilst not introducing excessive acoustic contamination. Our preliminary results show that those levels could be safely decreased with respect to the limits established by the European Union. In this way, these levels have been shown to be viable only in urban environments with moderate background noise. Its application in very quiet or very noisy scenarios has proven not to be optimal.

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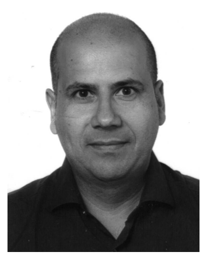
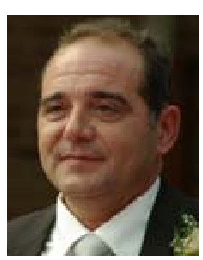
Ferran Mocholí Belenguer was born in Valencia, Spain, in 1992. He received the B.S. degree in telecommunications engineering and the M.S. degree in acoustic engineering from Universitat Politècnica de València, Spain, in 2014 and 2019, respectively. Since 2016, he has been a Research Assistant with the Group of Traffic Control Systems, ITACA Institute. His research interests include the development of new traffic sensors based on magnetic loops and laser technology, infrastructure homologation according to different standards, and magnetic characterization of vehicles.

Antonio Martínez-Millana received the Ph.D. degree in technologies for health and wellbeing from the Universitat Politècnica de València, Spain, in 2017. He is currently working as a Research Assistant with European e-Health projects in ITACA and lecturing with the Department of Electronic Engineering, Universitat Politècnica de València. His research interests include diabetes, mathematical modeling, biomedical engineering, and process mining.



Francisco Sales Castells Ramón received the Ph.D. degree in electronics engineering from the Universitat Politècnica de València (UPV), Spain, in 2006. He is currently an Associate Professor with the Department of Electronics Engineering, UPV. His research interests include acoustic engineering, electromagnetics, processing, and biomedical engineering.



Antonio Mocholí-Salcedo received the Ph.D. degree in industrial engineering from the Universitat Politècnica de València, Spain, in 1991. He is currently a Professor with the Department of Electronic Engineering, Universitat Politècnica de València. He is also the Coordinator of the Traffic Control Systems (STC) Group, ITACA Institute, Universitat Politècnica de València. His research interests include the development of new traffic sensors based on magnetic loops and laser technology, development of protocols for homologation of equipment, and development of V2V and V2V communications.