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THE SUITABILITY OF INTERNAL COMBUSTION ENGINE SOUNDS AS ARTIFICIAL WARNING SOUNDS FOR ELECTRIC AND HYBRID VEHICLES

ABSTRACT

The paper discusses the issue of adding artificial warning sounds to hybrid and fully electric vehicles in order to increase traffic safety by making these vehicles audible at low speeds. The goal of this modification is to enable the pedestrians to perceive possible danger coming from such a vehicle in time to respond accordingly. Following the results of previous research which state that the sounds of internal combustion engines are valid candidates for artificial warning sounds, a preliminary examination of the suitability and acceptability of different engine sounds in various modes of operation has been conducted. The chosen modes of operation are running in idle, at 2,000 rpm and 3,000 rpm with the vehicle stopped. Both gasoline and diesel engines were investigated. To expand the range of engine sounds, the type of vehicles was not limited to personal cars. The results show significant differences in suitability of engine sounds for the stated purpose, with vehicle type being the main differentiating factor.

KEY WORDS

artificial warning sounds; electric and hybrid vehicles; traffic safety; traffic noise

1. INTRODUCTION

In modern day vehicles of classic design, i.e. with an internal combustion (further in the text IC) engine as the propulsion unit, two major noise components contribute to the overall noise emissions: the propulsion noise generated by the engine itself (including IC engine fan noise [1]) and the rolling noise generated by the tyres in contact with the roadway as well as aerodynamic noise due to air resistance. At low speeds, generally below 30 km/h, the propulsion noise is dominant, while rolling noise prevails above the stated speed [2]. On the other hand, in hybrid vehicles equipped with an IC engine and an electric motor, the IC engine is (in most cases) used at speeds above 20 km/h, and in fully electric vehicles only the electric motor is used as a means of propulsion. In both cases, the propulsion noise component is absent at low speeds. The fact that the rolling noise is low at these speeds leads to the conclusion that the overall noise emissions of such vehicles are low as well.

The reduction of noise level of hybrid and electric vehicles at lower speeds, compared to vehicles with IC engines, raises the concern about road traffic safety, especially for pedestrians and cyclists, who rely greatly on sound stimuli while moving in traffic [3, 4]. The lack of familiar engine sounds in city traffic especially affects the blind and the visually impaired [2, 5, 6].

The findings of the study described in [3] confirm the statistically significant difference between the hybrid electric and IC engine vehicles and their involvement in traffic accidents under certain circumstances. Specifically, hybrid electric vehicles are more often involved in accidents with pedestrians and cyclists on roadways, in zones of low speed limit during the day and in clear weather. The risk for such a vehicle to be involved in an accident during low-speed manoeuvres such as slowing down, stopping, driving in reverse, and entering or exiting a parking spot is twice as high as the one reported for IC engine vehicles. Additionally, hybrid electric vehicles have a higher risk of being involved in an accident if the vehicle is turning, while moving straight bears no significant difference.

In [2], an analysis was performed on the time available to pedestrians and cyclists to react to an oncoming vehicle that is out of direct sight. The conclusion was drawn that the available reaction time for pedestrians and cyclists is significantly shorter in case of hybrid electric vehicles at low speeds, whereas the difference in available reaction time between the two vehicle types becomes insignificant with the increase of speed, all of which can be directly ascribed to the described differences in sound emission. These findings were confirmed by a similar study [7].

To overcome the potential traffic safety hazard caused by excessively low sound emissions from hybrid and fully electric vehicles at low speeds, artificial sound source(s) can be added as an integral part of such a vehicle, which would then serve as a warning to pedestrians and cyclists [2]. Viewed as the best solution to the problem at hand [5], it has lead to passing draft laws on establishing the standards stipulating the obligatory introduction of sound sources below cross-over speed of hybrid and electric vehicles [8]. The cross-over speed is defined as the speed at which the rolling noise and other factors eliminate the need for a separate artificial sound source. Similar legislative is being considered elsewhere as well [2, 9]. On the other hand, the potential for noise reduction in urban areas introduced by the use of electric vehicles cannot be denied. A certain fear arose that the described solution would cancel these efforts [10] and lead to a change in soundscape, which would now be dominated by artificial sounds [2].

The research data in this particular field are fairly limited, as this is a relatively new issue to be dealt with. A simple survey described in [11] tried to give some answers to questions related to this issue. The results showed that the lack of engine sound in hybrid and electric vehicles is generally considered a potential threat to pedestrians. It has also been found that the sound of a vehicle makes people more aware of the speed and position of the vehicle and that people rely greatly on sound stimuli when crossing a road or a street. Furthermore, almost half of the investigated people expressed concern about being pedestrians in traffic together with completely silent vehicles. One third expressed discomfort about the idea of being the drivers of such vehicles. It was generally agreed that adding sound to silent vehicles would make them safer for pedestrians. The second part of the survey dealt with the suitability of different sounds. There were 40% examinees who found the sound of the IC engine and hum to be the most appropriate ones, while 11% considered that no sound was appropriate.

The study described in [12] tested the suitability of different sounds, and white noise was added to the list of acceptable sounds. In continuation, actual sounds were presented together with a video recording of a hybrid vehicle. Again, engine noise was found to be the most suitable sound, followed by white noise and hum. The sounds of a siren and a horn were perceived as unsuitable.

The study described in [13] investigated the detection distance for hybrid vehicles moving at low speed, depending on the artificial sound the vehicle was equipped with. The chosen sounds were the artificial sound of an IC engine, the artificial sound of the engine with the periodical bell sound added to it, and no additional artificial sound. The results showed a significant difference in the detection distance between the no sound and the engine sound condition. Specifically, the test subjects were able to detect the vehicle at a much greater distance when it was equipped with the artificial engine sound. The additional bell sound did not contribute to further increase of the detection distance and was perceived as unsuitable. In the second part of the study, the vehicle detection threshold was investigated in relation to the level of background noise. It was found that the sound pressure level of sound produced by the vehicle has to be at least 2 dB higher than the background noise level for the vehicle to be detected. It was also suggested that a compromise can be reached between noise pollution on one hand and the effort to give a loud enough warning to pedestrians on the other by using directional sound emission from the vehicle.

As a logical continuation and extension of the research described above, the work carried out in this research is focused on investigating the suitability and acceptability of IC engine sounds and the potential for using them as artificial warning sounds for electric and hybrid vehicles. The hypothesis set in the research is that not all engine sounds will be viewed as equally suitable for this purpose. For this reason, a listening experiment was designed to determine people's preferences. The results are to be used in future research related to the design and optimization of acceptable and functional warning sounds.

2. THE LISTENING EXPERIMENT

Listeners

A total of 24 listeners took part in the experiment; 13 of them were male and 11 were female. The age range was 17 to 58, with the mean value of 33.5 and standard deviation of 9.3 years. The listeners were recruited entirely on voluntary and pro bono basis. None of the listeners reported any hearing damage.

Stimuli

In this experiment the emphasis was put on the differences between sounds generated by various types of internal combustion (IC) engines. Since any kind

Table 1 - The vehicles and their respective engines chosen for the experiment

Vehicle No.	Vehicle type	Manufacturer	Model	Engine displacement (cm^3)	Engine type
1	Personal	Chevrolet	Cruze	1,600	Gasoline
2	Delivery van	Ford	Transit	2,200	Diesel
3	Personal	Peugeot	308 SW	2,000	Diesel
4	Personal	Renault	Scenic	1,600	Gasoline
5	Personal	Renault	Thalia	1,400	Gasoline
6	Personal	Renault	Twingo	1,200	Gasoline
7	Motorcycle	Yamaha	TDM 900	900	Gasoline

of engine sound has the potential to be used in the sound design process, the decision was made to include engine sounds of other vehicles as well, rather than limiting the investigation to engine sounds of personal cars.

As the final choice, seven vehicles and their respective engine sounds were included in the experiment, as shown in *Table 1*. Five vehicles belong to the category of personal cars, one vehicle is used for transport and delivery and the last vehicle is a motorcycle. The vehicles were selected to obtain a diverse choice of vehicle sizes, engine displacements and engine types.

The sound samples used in the test were obtained by recording the engine sounds using the artificial head aided with binaural microphone pair and a portable two-channel recorder. To minimize the background noise of any kind, the recording procedure was carried out on an abandoned road in a forest, far away from the city. The artificial head was placed at the side of the road with its "ears" at the height of 1.15 metres. The vehicles whose sounds needed to be recorded were then allowed to park in front of the artificial head at a distance of 1 metre, so that the front wheel of the vehicle was right in front of the artificial head. The recording setup is shown in *Figure 1*.

The following engine sounds were recorded: the sound of ignition and engine running in idle (750 – 850 rpm for most engines), engine running at 2,000 rpm and, finally, engine running at 3,000 rpm. To avoid compression artefacts, the sounds were recorded in an uncompressed PCM format with the sampling frequency of 44.1 kHz in 16-bit resolution. A continuous recording was made with a constant gain setting to preserve the information on the level difference between the sounds of different engines. Absolute sound pressure levels were measured with a sound level meter.

Further processing of the raw recording was made on a computer by freeware capable of wav editing. To obtain the highest possible level without clipping, the recording was amplified using peak normalization and then the individual samples were cut out. The first group of samples are 13-second samples which contain the ignition sound and the sound of the engine running in idle mode. The remaining two groups contain 8-second sound samples of the engines running at 2,000 and 3,000 rpm.

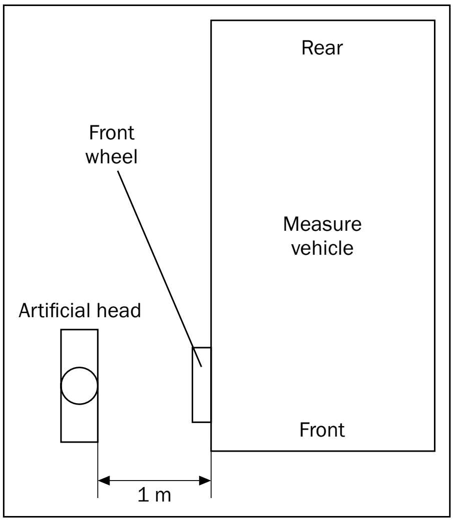

Figure 1 - Recording setup

Procedure and task

The listeners took the test one at a time using a reproduction system that consisted of a laptop computer and a pair of high-quality closed headphones capable of providing 32 dB of sound insulation. The level setting was kept constant throughout the experiment.

Each group of sounds described earlier was presented to the listeners separately. The sounds of ignition and running in idle were presented first, followed by the sounds of engines running at 2,000 and 3,000 rpm. All sounds in a given group were presented to the listeners before the evaluation. That way the listeners could familiarize themselves with the entire range of sounds they will be evaluating. After familiarization, the sounds were played in a sequence, allowing the listeners to evaluate their suitability. The chosen range of grades was 1 to 10, where 1 marked a completely unsuitable sound while 10 represented a perfectly suitable sound. The listeners were instructed not to evaluate the sounds based on their preferences on a suitable sound for a single vehicle. Instead, they were asked to imagine a situation in which all vehicles in traffic produced the same sound, i.e. the sound they were evaluating, and to evaluate its suitability accordingly. To avoid bias, no information about the vehicles was given to the listeners. To minimize the possibility of systematic errors occurring in the experiment, the reproduction sequence within each group was randomized, and each listener listened and evaluated the samples in an entirely individualized sequence.

3. SINGLE-NUMBER OBJECTIVE PARAMETERS

To describe the engine sounds included in the experiment in an objective manner, the recorded sounds were analyzed using well-known models developed for the calculation of psycho-acoustical parameters. Four main groups of single-number parameters were defined; namely, parameters related to the amount of acoustic energy, spectral properties of sound, the amount of fluctuations and tonal properties.

The parameters related to the amount of acoustic energy (sound power) are sound pressure levels, A-weighted and unweighted, and the loudness calculated according to Chalupper and Fastl [14] and Moore and Glasberg [15]. The parameters related to the overall spectral shape are the spectral centroid, and Zwicker and Aures sharpness [16, 17] as the measures of high-frequency content in a sound. The amount of both fast and slow fluctuations in a sound was represented with roughness by Daniel and Weber [18] and Chalupper loudness fluctuation [19], respectively. Tonal properties of sounds were examined by calculating pure and complex tonalness with the Terhardt model [20]. All used models give time-dependant values of parameters as the output, so median values obtained for the entire samples were used as single-number values. Since the engine sounds of interest were considered to be stationary, it was decided not to perform a statistical analysis of the obtained time-dependant values of objective parameters.

Apart from the single-number parameters, the spectra of all the sounds included in the investigation were calculated and analyzed as well.

4. RESULTS AND DISCUSSION

The results of the investigations are shown in three subsections. The first subsection presents the results of statistical analysis performed on subjective responses. The second one gives the overview of objective parameters calculated for all sounds included in the experiment. The third subsection shows the correlation between the objective parameters and the grades obtained through subjective evaluation and investigates its statistical significance.

Subjective evaluation

The results obtained from the listening experiment were analyzed in several steps. To determine whether or not all the listeners have understood and used the grading scale in a similar manner, the original grades given by the listeners were analyzed through ANOVA test. All grades given by each listener were taken into account, assuming that the evaluation criteria set by each listener for themselves were maintained throughout the experiment. The results of this test have shown that there are indeed statistically significant inter-individual differences, with $F(23,480) = 3.053$, $p < 0.001$. To solve this, the original grades were standardized for each listener by subtracting the mean value of their grades from an individual grade and dividing that difference with standard deviation, again assuming that the listeners used the grading scale consistently throughout the experiment. The obtained grades, both original and standardized, are shown in Tables 2 and 3 as arithmetic means calculated over all 24 listeners. Standard deviations are shown as well. For a better overview, the results are presented graphically as well as in Figures 2 and 3.

After standardization, the responses to engine sounds in each of the three modes of operation were analyzed separately through a series of ANOVA tests. The tests were performed to determine if there were statistically significant differences between the perceived suitability of these engine sounds as artificial warning sounds, as evaluated by the listeners. The re-

Table 2 - Original grades as obtained from the experiment, given as mean values and standard deviations

Vehicle	Original grades					
	Idle		2,000 rpm		3,000 rpm	
	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation
1	7.17	1.90	7.08	1.84	5.71	1.92
2	4.21	1.93	2.38	1.58	1.79	1.25
3	6.25	1.92	5.96	1.55	6.42	1.93
4	7.58	1.41	7.63	1.84	6.33	1.63
5	5.04	2.31	6.08	1.95	5.88	1.54
6	6.79	2.25	6.38	2.46	6.79	2.21
7	2.00	1.67	1.92	1.59	1.63	1.47

Table 3 - Standardized grades given as mean values and standard deviations

Vehicle	Standardized grades					
	Idle		2,000 rpm		3,000 rpm	
	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation
1	0.73	0.66	0.69	0.58	0.14	0.51
2	-0.39	0.70	-1.13	0.43	-1.37	0.30
3	0.40	0.51	0.30	0.57	0.46	0.72
4	0.90	0.55	0.89	0.54	0.37	0.41
5	-0.01	0.81	0.28	0.54	0.20	0.44
6	0.56	0.71	0.37	0.73	0.54	0.64
7	-1.24	0.68	-1.27	0.70	-1.40	0.78

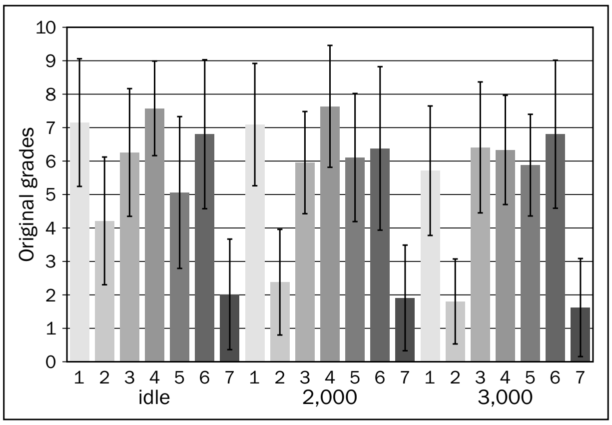

Figure 2 - Original grades obtained for all seven vehicles in all three modes of operation. Mean values are represented with columns, and the error bars represent the range of ±1 standard deviation

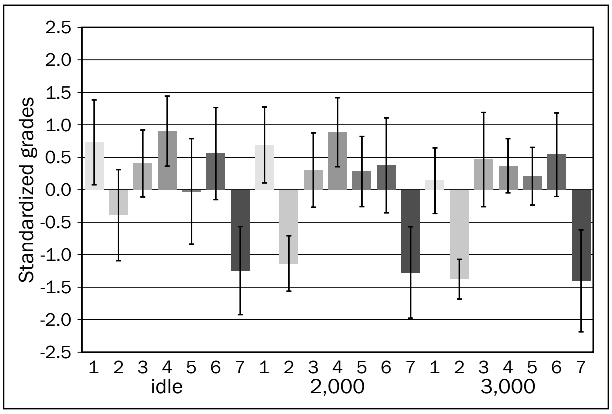

Figure 3 - Standardized grades obtained for all seven vehicles in all three modes of operation. Mean values are represented with columns, and the error bars represent the range of ±1 standard deviation

sults of these tests have confirmed that statistically significant differences do exist in all three cases, namely, $F(6,161) = 30.24$, $p < 0.001$ for engine sounds in idle mode, $F(6,161) = 51.05$, $p < 0.001$ for sounds of engines running at 2,000 rpm and $F(6,161) = 54.45$, $p < 0.001$ for sounds of engines running at 3,000 rpm.

As ANOVA test revealed the existence of significant differences in a group of sounds, but does not provide data on the exact sounds that significantly differ from each other, a post-hoc test must be applied as well. In this case Tukey tests were performed to complement the results of ANOVA tests. The chosen significance level was 0.05.

For the sounds of engines running in idle mode, several significant differences were found, thereby allowing the forming of a preference list. Specifically, the suitability of sound 7 is significantly lower than of all the other ones. Sound 2 also differs significantly from the other ones in the group, i.e. its suitability is higher than for sound 7, but lower than for all the others except sound 5, so the two can be put into the same subgroup of sounds. The suitability of sounds 1 and 4 is the highest and significantly differs from the suitability of sounds 2, 5 and 7, leaving sounds 3 and 6 in the subgroup with the second highest suitability.

For sounds of engines running at 2,000 rpm, the suitability of sounds 2 and 7 is significantly lower than for all the other ones, whereas sound 4 is evaluated as the most suitable and differs significantly from all the other sounds except sound 1 as the second most suitable one. Sounds 3, 5 and 6 are found between the extremes, and differ significantly from sounds 2 and 7 on one hand and sound 4 on the other.

Finally, for sounds of engines running at 3,000 rpm, the suitability of sounds 2 and 7 is again evaluated as significantly lower than for all the other ones, while the remaining sounds do not differ significantly among themselves.

Objective analysis

Using the models for calculating the objective parameters listed in Section 3, the single-number values of these parameters were obtained, as listed in *Table 4*.

The data shown in *Table 4* reveal a great variety of sounds included in the listening experiment, regarding their basic physical and psycho-acoustical properties described with appropriate parameters. The range of unweighted sound pressure levels exceeds 40 dB, and all the A-weighted ones can be placed within a 30 dB interval. Expressed in terms of loudness, the ratio of loudness of the loudest and the softest sound reaches between 6 and 7, depending on the loudness model used for analysis. In any case, a wide range of sound power of various engines running in three different regimes results in the observed changes in sound pressure level and loudness and is expected to have a profound influence on the perception of these sounds. The values of Zwicker sharpness are generally lower than the ones observed in previous studies on the machinery-generated noise [21]. In this case the contribution of low frequency content to the overall spectrum is considerable, whereas in previous research the low frequency content of investigated sounds was negligible. It is interesting to notice that the changes in loudness-dependant Aures sharpness do not follow the changes in loudness in the extent observed in previous research. Besides loudness and sharpness, the amount of fluctuations in a sound was found to be one of the properties of sound with major influence on the perception of both the machinery sounds and the sources that generated them. Given the typical operation cycle of an engine, it is expected that rapid fluctuations present in a sound, represented with objective roughness, will profoundly influence the way engine sounds are perceived. Slow fluctuations described with loudness fluctuation are emphasized in the sound of vehicle No. 7, i.e. the motorcycle, especially when running in idle mode and at 2,000 rpm, given the highly impulsive nature of its sound. Finally, tonal properties represented with pure and complex tonalness generally become more pronounced with the increase of rotational speed. As such, the lowest values were observed for sounds of engines running in idle mode, which in general have a noise-like character. As the rotational speed of the engine increases, the tonality of the overall sound increases and is determined by the amplitudes of the fundamental frequency component and its harmonics.

The spectra of all the sounds are shown in *Figure 4*. The lowermost lines in the charts show the spectra of engine sounds in idle mode, the middle ones represent the spectra of sounds emitted by engines running at 2,000 rpm, whereas the uppermost lines display the spectra of engine sounds at 3,000 rpm. The spectra calculated for sounds in idle mode maintained accurate levels, and the spectra of sounds at 2,000 and

Table 4 - Single-number values of objective parameters describing the engine sounds

Vehicle	Mode of operation	Loudness Chalupperr (sone)	Loudness Moore (sone)	Sound pressure level LAF (dBA)	Sound pressure level LZF (dBZ)	Spectral centroid (Hz)	Sharpness Aures (acum)	Sharpness Zwicker (acum)	Roughness (asper)	Loudness fluctuation ()	Pure tonalness (tu)	Complex tonalness (tu)
1	idle	9.29	15.10	54.1	58.5	1,390	3.37	1.71	0.03	0.50	0.19	0.03
2	idle	21.40	32.56	67.7	81.2	338	4.77	1.90	0.25	0.66	0.21	0.02
3	idle	14.02	21.44	61.6	73.3	138	3.05	1.46	0.12	0.65	0.21	0.02
4	idle	8.81	14.28	54.0	58.6	727	3.03	1.58	0.03	0.60	0.18	0.02
5	idle	11.53	18.27	57.9	66.6	369	3.24	1.59	0.06	0.73	0.18	0.02
6	idle	8.93	14.62	53.7	75.8	46	3.27	1.67	0.08	0.74	0.20	0.03
7	idle	33.95	42.68	73.4	95.8	70	3.88	1.42	0.54	1.32	0.26	0.03
1	2,000	20.70	31.00	65.8	72.9	731	4.23	1.73	0.03	0.38	0.44	0.07
2	2,000	42.03	61.30	79.7	82.4	3,452	6.39	1.96	0.09	0.39	0.48	0.06
3	2,000	30.58	42.58	71.6	86.1	141	4.08	1.50	0.04	0.36	0.47	0.07
4	2,000	20.60	31.93	67.3	69.6	1,545	4.21	1.71	0.04	0.36	0.39	0.06
5	2,000	24.82	36.67	69.9	74.3	906	4.22	1.66	0.04	0.41	0.49	0.08
6	2,000	18.98	29.52	66.2	70.0	1,075	4.12	1.72	0.04	0.54	0.38	0.05
7	2,000	51.63	60.35	80.9	99.7	100	4.33	1.36	0.51	1.22	0.28	0.03
1	3,000	31.64	47.62	74.4	76.5	1,628	4.98	1.73	0.07	0.32	0.83	0.17
2	3,000	55.74	81.27	85.1	86.4	4,222	7.51	2.00	0.10	0.32	0.45	0.06
3	3,000	39.20	55.82	76.9	83.8	523	4.87	1.59	0.04	0.29	0.54	0.08
4	3,000	35.04	50.49	75.8	79.1	1,099	4.95	1.68	0.03	0.33	0.79	0.13
5	3,000	34.36	49.87	75.4	79.1	1,113	4.92	1.70	0.06	0.34	0.54	0.08
6	3,000	28.78	43.34	72.4	75.2	1,830	5.10	1.82	0.04	0.35	0.51	0.08
7	3,000	63.04	74.85	84.5	101.8	112	5.10	1.45	0.20	0.62	0.27	0.03

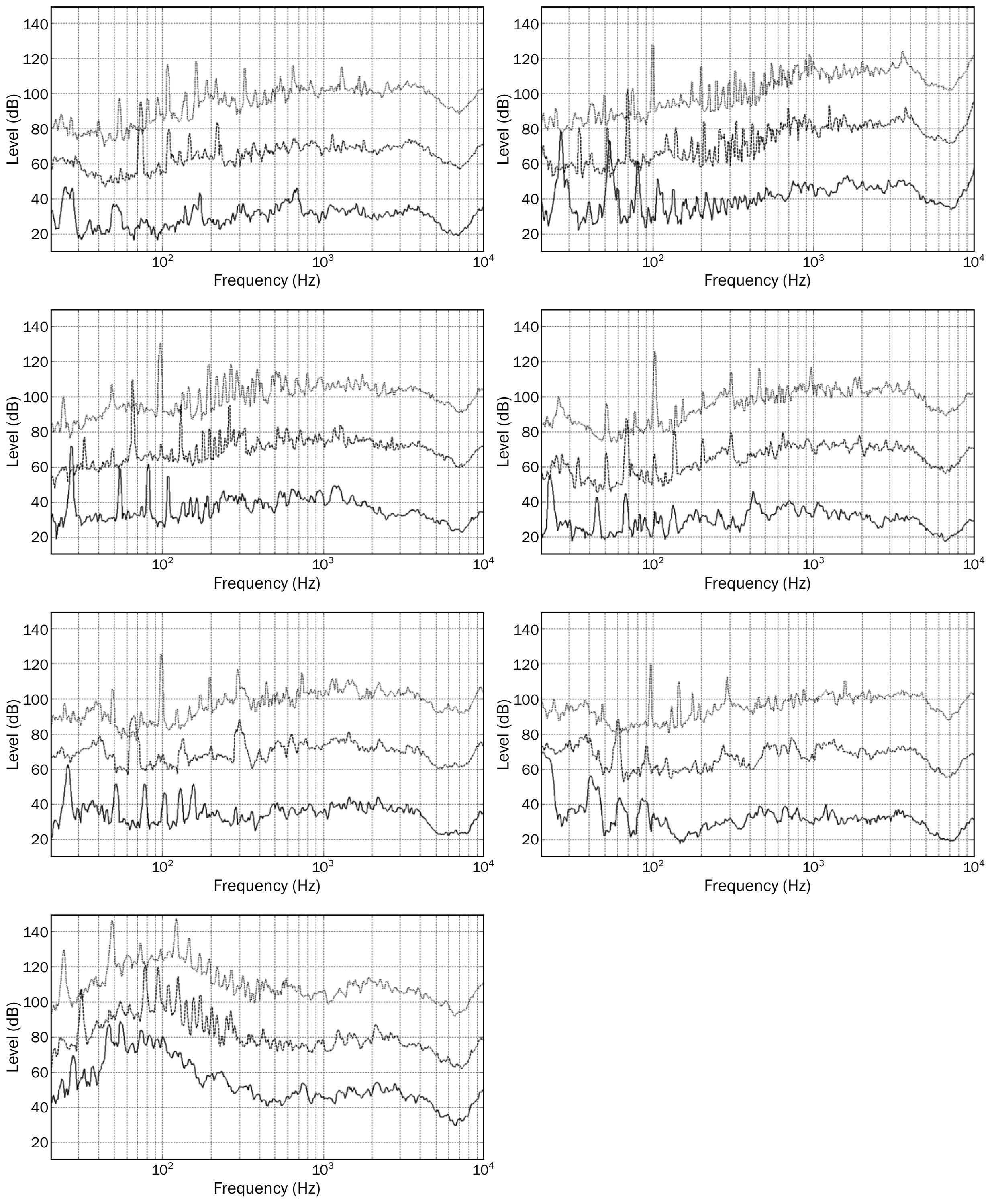

Figure 4 - Spectra of all the sounds in idle mode (bottom full line – accurate level), at 2,000 rpm (middle dashed line – shifted up by 25 dB) and 3,000 rpm (top dotted line – shifted up by 50 dB): 1 (top left), 2 (top right), 3 (mid left), 4 (mid right), 5 (low left), 6 (low right) and 7 (bottom left).

3,000 rpm have been shifted vertically by 25 and 50 dB, respectively, for better visibility.

The spectra of sounds recorded for all three modes of operation show distinct frequency components directly related to the rotational speed of the engine and the number of cylinders in it. Specifically, 4-cylinder engines in vehicles 1-6 with two explosions per each revolution of the crankshaft generate fundamental frequencies in the vicinity of 25 Hz, which corresponds to a rotational speed of 750 rpm. At 2,000 and 3,000 rpm, the fundamental frequencies are found at 66.6 Hz and 100 Hz, respectively. Besides fundamental frequencies, their harmonics can also be observed in the spectra. Subharmonic components are present as well, namely the 2nd subharmonics at 33 Hz and 50 Hz, respectively, as well as the 4th subharmonic at 25 Hz for sounds of engines running at 3,000 rpm. A pronounced fourth subharmonic at 16 Hz was observed for vehicles 2 and 3 with diesel engines running at 2,000 rpm, although it cannot be seen in the charts. Additionally, the spectra of sounds of these two engines running at 2,000 and 3,000 rpm show prominent tonal components in the frequency range from 150 – 500 Hz which are the result of intermodulation, whereas such components are not visible for gasoline engines 1, 4, 5 and 6. It was also observed that the sounds of diesel engines have more prominent tonal components in idle mode than gasoline engines.

The sound of the motorcycle engine (vehicle 7) shares some of the spectral properties with other investigated engine sounds, namely the prominent tonal components. Due to a 2-cylinder assembly with one explosion per revolution of the crankshaft, the fundamental frequency in this case is an octave lower, namely 33 and 50 Hz if the engine is running at 2,000 and 3,000 rpm, respectively. Harmonic and subharmonic components, as well as prominent intermodulation components are present in the spectrum. However, the overall spectral shape of this particular engine sound shows a major difference in comparison with other investigated engine sounds. The low-frequency content in the spectrum is excessively emphasized, most likely by design in this case, and the overly elevated levels of low-frequency components are maintained in all three investigated modes of operation. On the other hand, the spectra of other engine sounds reveal a flat overall spectral shape in idle mode, apart from prominent tonal components. Furthermore, the increase in rotational speed leads to shifting the energy content towards higher frequencies, thus rendering the low-frequency content unimportant and not perceivable in the overall sound.

The correlation between subjective grades and objective measures

Finally, the relationships between objective psycho-acoustical parameters that describe the engine sounds and the subjectively evaluated suitability have been investigated by means of Pearson correlation. The correlation coefficients were calculated for each mode of operation separately, as well as for all three modes of operation combined, as shown in *Table 5*. Statistically significant correlation coefficients are marked according to the significance level, namely, 0.05, 0.01, 0.001 and 0.0001.

The results of the correlation analysis show that the amount of acoustic energy emitted by an IC engine, i.e. its sound power has the strongest influence on the perception of suitability of the sound of such an engine as an artificial warning sound. All parameters displaying sound pressure levels and loudness are in statistically significant correlation with subjective evaluations of suitability at different significance levels, as shown in *Table 5*. Parameters related to the overall spectral shape, i.e. sharpness and spectral centroid do not appear to be relevant for the perception of suitability, and the same conclusion can be drawn for tonality-based parameters. On the other hand, the amount of fluctuation in an engine sound has an influence on perception of its suitability, as shown with statistically significant correlation coefficients between objective roughness and loudness fluctuation on one side and the evaluated suitability on the other.

Table 5 - Pearson correlation coefficients between objective parameters and subjective grades

Objective parameter	Mode of operation			
	Idle	2,000 rpm	3,000 rpm	All
Loudness (Zwicker)	-0.952[iii]	-0.947[ii]	-0.945[ii]	-0.776[iv]
Loudness (Moore)	-0.953[iii]	-0.958[iii]	-0.946[ii]	-0.724[iii]
Sound pressure level LAF	-0.938[ii]	-0.964[iii]	-0.955[iii]	-0.696[iii]
Sound pressure level LZF	-0.890[ii]	-0.800[i]	-0.809[i]	-0.804[iv]
Spectral centroid	0.513	-0.271	-0.330	-0.220
Sharpness (Aures)	-0.645	-0.629	-0.663	-0.558[ii]
Sharpness (Zwicker)	0.185	0.111	-0.045	0.041
Roughness	-0.935[ii]	-0.735	-0.867[i]	-0.697[iii]
Loudness fluctuation	-0.855[i]	-0.649	-0.622	-0.462[i]
Pure tonalness	-0.832[i]	0.303	0.646	0.100
Complex tonalness	-0.149	0.590	0.588	0.196

Statistically significant at 0.05[i], 0.01[ii], 0.001[iii] and 0.0001[iv] level

5. CONCLUSION

The research shows evident differences in acceptability of different IC engine sounds which could be potentially used as artificial warning sounds for hybrid and electric vehicles. The results of the investigation lead to the conclusion that the loudness of a sound of an IC engine is the determining factor for it to be accepted as a suitable candidate to be used as an artificial sound of an electric/hybrid vehicle. This result was expected, having in mind the exact nature of the task given to the listeners, i.e. to evaluate the acceptability of an engine sound assuming that all vehicles in traffic would be equipped with a source of such a sound, rather than just a single vehicle. Excessively strong fluctuations in an engine sound are viewed as an undesirable property as well, thereby confirming the results of previous research performed sound quality of power tools, in which such fluctuations were perceived as a sign of malfunction. The results of objective analysis of engine sounds go in favour of sounds of gasoline engines over diesel powered ones. Furthermore, engine sounds with a well-balanced frequency spectrum are evaluated as more acceptable. The sounds that have been made excessively loud by design or some other undesirable property has been emphasized, e.g. excessive fluctuations, are considered to be unsuitable.

Future work is to address in detail the desirable and undesirable features of IC engine sounds, thus making them more or less acceptable for the desired purpose. To remove the influence of loudness as the most prominent characteristic of sound, the loudness of the samples is to be normalized in future listening experiments.

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SAŽETAK

PRIKLADNOST ZVUKOVA MOTORA S UNUTARNJIM IZGARANJEM KAO UMJETNIH ZVUKOVA UPOZORAVANJA ZA ELEKTRIČNA I HIBRIDNA VOZILA

U radu se govori o problemu dodavanja umjetnih zvukova upozoravanja hibridnim i potpuno električnim vozilima s ciljem povećanja sigurnosti prometa, čime takva vozila postaju čujna i pri malim brzinama kretanja. Time je pješacima omogućeno pravovremeno uočavanje potencijalne opasnosti koju takvo vozilo predstavlja. Na temelju prijašnjih istraživanja koja zvukove motora s unutarnjim izgaranjem svrstavaju među legitimne potencijalne zvukove upozoravanja koje treba dodati hibridnim ili električnim vozilima, provedeno je preliminarno ispitivanje prikladnosti i prihvatljivosti zvukova motora u različitim režimima rada. Konkretno, uzeti su zvukovi motora pri radu u praznom hodu te na dvije i tri tisuće okretaja u minuti, dok je vozilo zaustavljeno. U obzir su uzeti i benzinski i dizelski motori. Radi povećanja broja i raznolikosti zvukova motora, istraživanje nije ograničeno samo na osobna vozila. Rezultati istraživanja otkrivaju značajne razlike u prikladnosti zvukova motora u navedenu svrhu, pri čemu upravo tip vozila predstavlja glavni utjecajni čimbenik.

KLJUČNE RIJEČI

umjetni zvukovi upozoravanja; električna i hibridna vozila; sigurnost prometa; buka prometa

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