

Acoustic Directivity and Detectability of Electric Powered Two-Wheelers

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Summary

Since motorcycles are one of the main sources of noise in urban environments, the use of electric powered two-wheelers may contribute to the improvement of soundscapes in Smart Cities. However, quiet vehicles can lead to an increased risk of accident for pedestrians and other drivers. In order to assess the noise generated by powered two-wheelers and their detectability five different low capacity motorcycles were measured in a pass-by noise test. The measurements were performed at different speeds using a linear microphone array and a dummy head. The sound directivity radiated by the moving sources was studied with a microphone array. To establish the detectability of powered two-wheelers, thirty-seven subjects participated in an auditory test consisting on a virtual road-crossing scenario. The subjects had to detect the approaching of a vehicle at 20 km/h. The results showed a significant reduction in the sound pressure level emitted by electric motorcycles at low-speed, as well as a notable increase in sound directivity with velocity. The reaction time obtained for the detection of electric powered two-wheelers was higher compared to the traditional propulsion ones. The results highlighted the risk posed by this kind of electric vehicles for pedestrians.

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1. Introduction

The use of electric engines has been a significant change in the acoustic behaviour of vehicles. This has encouraged the scientific community to explore this propulsion system, analysing the validity of the current noise, vibration and harshness (NVH) prediction and characterization tools. In accordance with [1], 20 million electric vehicles (EV) were estimated all over the world in 2020. Prospects have been reduced due to the high price of batteries and the global economic situation. At the end of 2014 there were about 665,000 electric four-wheel passenger vehicles, which represents a 0.08% of the total vehicles. Attention should also be drawn to the existing stock in China, with 230 million of e-bikes and 36,500 e-buses [2].

Electric vehicles represent a significant reduction of environmental pollution in cities. The decrease of the gases emitted by this kind of vehicle is a clear advantage compared with the traditional vehicles. Moreover, the decrease of vibrations provided by the engine due to the absence of reciprocating and rotational masses inside, can lead to a considerably decrease of noise. In general, EVs are powered by DC batteries. The voltage provided by the cells

is transformed into a magnitude and frequency controlled AC signal by means of an inverter using pulse-width modulation (PWM). The switching frequency to generate the PWM, together with the magnet noise from the electric powertrain, are two of the main contributions to the noise emitted by EVs. The fans used for batteries may be considered as another source of noise in EVs. The decrease of the sound pressure level emitted by EVs in comparison with internal combustion engine vehicles (ICEV) is clearly evident at speeds below 50 km/h. In this case, the global noise from the vehicle is dominated by the sound produced by the propulsion system. At speeds above 50 km/h, the noise generated by the tyre-road contact and the aerodynamics of the vehicle becomes more important. At this situation, the noise emitted by EVs and ICEVs matches as illustrated in [3]. The study compares the sound pressure level generated by different vehicles depending on the speed. Similar results were obtained in [4, 5] comparing different propulsion systems.

The reduction of noise may have a positive impact in health terms, since nearly 20,000 people die each year because of disease resulting from noise [6]. The use of EVs may significantly change the soundscapes in urban environments. However, quiet vehicles constitute a disadvantage from the road safety point of view. Since EVs are more complicated to detect, the risk of an accident in-

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creases for pedestrians, cyclists and other road users. L. Garay *et al.* in [7] show the increase in the pedestrian response time in the presence of an EV and similar results are obtained in [8]. According to [9], a hybrid electric vehicle (HEV) is twice more likely to be involved in a pedestrian crash than an internal combustion engine vehicle in the same situation. In order to improve the detectability of four-wheel EVs, some government administrations have established the need of an Acoustic Vehicle Alerting System (AVAS) into the vehicles. These systems may emit sounds, under some speed conditions, to alert pedestrians of the presence of a vehicle without increasing the environmental noise pollution. The use of these devices has already been discussed in the literature. K. Yamauchi compares in [10] the level of different warning sounds to be detected in a number of urban background noises. E. Parizet *et al.* study in [11] the detectability of different designed warning sounds comparing the reaction time (RT) between people with normal vision and people visually impaired. These works underscore how useful the warning sounds can be to improve the detectability of four-wheel electric vehicles.

At present, different countries are working on the development of new regulations related to AVAS [12, 13, 14]. First drafts define both the characteristics of the emitted noises as the traffic conditions where they must be activated. Recommendations establish the use of sounds that emulate the noise generated by ICEVs. Also, the system must remain active for speeds below 30 km/h.

The aforementioned references, both normative and scientific, refer exclusively to four-wheel vehicles. The acoustic behaviour of electric powered two-wheelers (ePTWs) has not been studied in depth. The use of motorcycles is being increased all over the world, becoming a very useful mobility tool in urban areas [15]. According to [16], it is estimated that there is a total of 313 million of two-wheel vehicles in the world. Additionally, it is foreseen that in 2040, powered two-wheelers (PTWs) represent the 35% of the total sales of vehicles [17].

According to [18], almost half of road traffic deaths take place between pedestrians, cyclists and motorcyclists. Statistically analysing the accidents occurred during the last years in which PTWs were involved, approximately the 57% of moped accidents and the 39% of accidents for high capacity motorcycles took place in urban areas [19]. One of the main causes of PTW crashes is the low visibility of the vehicle. Because of its reduced size, PTWs are often hidden by the other road users [20]. In order to ensure the safety of drivers and pedestrians, this kind of vehicles are provided with different security systems [21]. On the one hand the braking system is enhanced using anti-lock braking systems (ABS). On the other hand, to increase the detectability of motorcycles, light-signalling devices and electronic detection equipment are introduced into the vehicle. Two-wheelers, due to their lower weight and smaller tyre-road contact surface, produce a rolling noise lower than that generated by four-wheel vehicles. Therefore, the participation of the noise emitted by the propulsion system

in the overall vehicle sound will be higher. Besides, taking into account their simpler power train [22], the noise generated at low speed regimens will be given by the engine. So it is conceivable, that noise reduction due to electric propulsion systems is quite pronounced. Joël Lelong *et al.* in [23] analyse the acoustic behaviour of eleven motorcycles in a pass-by test at a constant speed. Vehicles had different engine capacity and one of them corresponds to a pure electric motorcycle (EM). The results showed a reduction of the sound pressure level L_{Amax} between 10 and 15 dBA for the electric motorcycle. According to [24], 100% replacement of internal combustion two-wheel vehicles by electric motorcycles may involve a reduction of noise greater than 2 dBA. However, noise reduction entails a decrease on the detectability of vehicles. If we also take into consideration that the stopping distance of PTWs is higher than for four-wheel vehicles [25], the risk for drivers and pedestrians may increase significantly. In addition, PTWs with low capacity are used almost exclusively in urban areas, where speed is reduced and the problem of quiet vehicles has a greater impact.

However, not all the attention should be paid on the sound pressure level as a key factor in detectability. Sound directivity represents the directional features of a source and therefore, it plays an important role too. According to [26], the directivity index (DI) of a hemispherical source can be defined as the difference between the sound pressure level measured in a particular direction θ , and the average sound pressure level over the measurement surface. The directivity of a sound source is one of the parameters that must be considered to determine the effect of noise over a potential receiver, for instance, on traffic noise prediction models [27]. Some measurement techniques can be found on the literature to determine this parameter: stationary vehicle directivity [28]; moving sources [29]; vertical directivity for moving sources (trains [30, 31, 32], aircraft [33, 34], road vehicles [35]); horizontal directivity of road vehicles [36]. In order to determine the radiation pattern of the vehicles, the use of a linear microphone array during pass-by tests may be appropriate to detect the position and speed of the moving noise source [37] and therefore, to obtain the sound pressure level (SPL) for each angle suppressing background noise.

Due to the foregoing, the acoustic behaviour of PTWs in urban environments should be studied more in detail. This paper is a contribution to the acoustic study of these vehicles. The main objectives are: (1) to study the sound pressure level emitted by powered two-wheelers, comparing the noise produced by electric and internal combustion engine motorcycles (ICEM); (2) to determine the sound directivity of two-wheelers; (3) to establish the detectability of electric and internal combustion motorcycles.

2. Methods and materials

2.1. Task

This paper examines, for a group of PTWs with different propulsion systems, the variation of the sound pressure

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level with the speed. At the same time, horizontal directivity of each vehicle was determined by means of a microphone array in a pass-by test. Finally, the detectability of PTWs was determined from an auditory test carried out in a laboratory. The following sections describe in detail the procedure used during the tests.

2.2. Experimental Design

A group of five mopeds with different propulsion systems was selected to be studied: three PTWs with pure electric propulsion systems - EM1, EM2 and EM3; one PTW with 4-stroke internal combustion engine – ICEM1; and one hybrid engine motorcycle (HEM) – denote during the paper as HEM_{EMode} for electric mode and $HEM_{ICEMode}$ for internal combustion mode. EM1 had a brushless DC engine with power 0.74 kW, chain drive, a wheelbase of 1.221 mm and a weight of 37 kg. The motorcycle was equipped with 24" rims and 60-507 tyres according to the European Tyre and Rim Technical Organization (ETRTO). EM2 corresponded to an electric motorcycle with a brushless permanent magnet AC engine, a maximum power of 13 kW and single speed direct chain drive. Its wheelbase was 1.420 mm, with a 100/90-18 front tyre and a 120/80-17 rear tyre. This motorcycle had a weight of 147 kg. EM3 had a brushless hub 4kW engine. It had a weight of 85 kg, a wheelbase of 1.380 mm, 13" rims and 130/60-13 tyres. ICEM1 consisted of a 4-stroke engine scooter of 108 cc capacity and a weight of 114 kg. It was provided with chain drive and had a wheelbase of 1.275 mm. This motorcycle used a 90/90-12 front tyre and a 100/90-10 rear tyre. The hybrid motorcycle, HEM, was equipped with a Brushless DC electric motor of 1 kW and a 5.15 kW 4-stroke engine. It had a weight of 130 kg, a wheelbase of 1.240 mm and tyres 100/90-10 in both wheels. For HEM, the electric mode and the internal combustion mode were analysed separately, allowing to compare the behaviour of both systems with the same boundary conditions. The selected vehicles represented those low capacity motorcycles most common in urban environments. The main information regarding motorcycles has been summarised in Table I.

All PTWs were subjected to a pass-by test. To study the behaviour of the vehicles at different speeds, the tests were conducted at around 10, 20, 30, 40 and 50 km/h. The actual vehicle speed was determined by means of a set of photocells located on one side of the road. During the event, the L_{Amax} emitted by each motorcycle was measured using a Sound Level Meter B&K Type 2250. The device was situated at 3 m. from the traffic lane instead of the 7.5 m. specified by the normative method (see Figure 1). This modification is intended to obtain the SPL from the pedestrian point of view in a road-crossing scenario since this is one of the situations that greater risk entail for pedestrians. At the same time, the sound directivity was measured using a linear microphone array [37]. The system was composed of 9 omnidirectional microphones, B&K Type 4958, located perpendicularly to the track and 3 meters away from it. The microphones were connected to a multi-channel data acquisition system. All measurements took place on a traffic lane with a standard asphalt G20 + S20.

Table I. Main features of PTWs used during the study.

ID	Propulsion System	Power [kW]	Capacity [cc]	Tyre Model
ICEM1	ICE	5.96	108	90/90-12 100/90-10
EM1	E	0.74	49	60-507
EM2	E	13.00	125	100/90-18 120/80-17
EM3	E	4.00	125	130/60-13
HEM	ICE/E	5.15/1	125	100/90-10

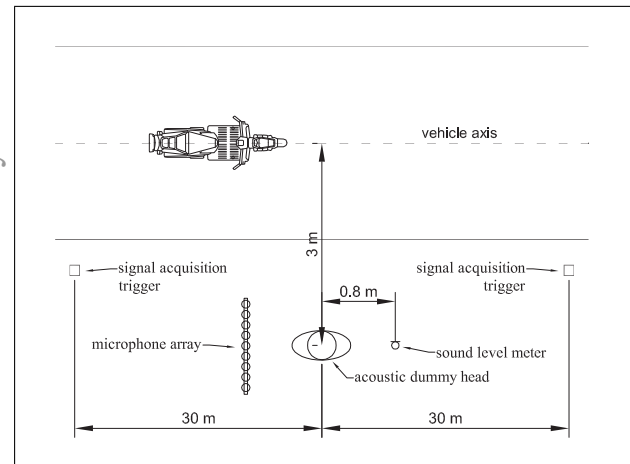


Figure 1. Pass-by test configuration.

To evaluate the detectability of PTWs, sound samples from each moped were obtained during the pass-by test. Recordings were made by means of a Head Acoustics HSM III dummy head, with a sample frequency of 44,100 Hz and a bit depth of 16 bits with noise shaping algorithm. A fifth order high-pass filter with cut-off frequency of 22 Hz was used during the acquisition. The dummy head was placed at a distance of 3 meters from the centre of the traffic lane, trying to simulate a real scenario: a pedestrian standing on the sidewalk, prepared to cross the road. The sound acquisition was made from ± 30 meters from the dummy head. Audio samples were used during the auditory tests in order to reproduce the sound event more accurately.

2.3. Sound directivity procedure

Assuming that during the pass-by tests the sound pressure level of a vehicle on a fixed height was measured, the directivity of the source was referenced to the plane of emission, being the directivity changing over the angle of radiation. During the tests, all the microphones captured the signal emitted by the source with a different delay according to the position of the source and the distance to the microphone. Subsequently, all signals were processed in a Double Cross-Spectrum (time-frequency domains) in order to detect the angle of emission of the noise source and the sound pressure level at different angles of emission [23].

During the signal processing, two important assumptions were made: 1) due to the distance between the source and the microphone array, the vehicle was considered to be in the far field region for frequencies below 2 kHz – minimum distance to far field calculated as the ratio between the squared wheelbase and four times the wavelength [38]; 2) the vehicles were moving along the track at constant speed.

2.4. Auditory detectability

2.4.1. Stimuli and background noise

As discussed in the previous section, a group of five motorcycles with different propulsion systems were measured. Table I describes the main feature of each PWT: identification (ID) during the paper (column 1); the propulsion system of each sample (column 2); the power of the engine (column 3); the capacity for ICEMs and the equivalent license capacity for EM (column 4); the weight of each motorcycle. For the HEM, electric and internal combustion modes were studied separately. Acquired sound samples were processed and conditioned to be used on the detectability tests. Samples were analysed and listened carefully in order to discard those useless. Some audio files presented different background noises that can somehow affect the validity of the samples and the detectability results: wind, birds, barking, aircraft or other vehicles. These samples were filtered or even removed. In order to eliminate a part of the signal fluctuations caused by wind, all samples were filtered by a 5-th order Butterworth high-pass filter with cut-off frequency of 80 Hz.

The binaural sound samples were obtained with an acoustic dummy head using free field equalization. This equalization allows to correct the effect of the head in the acquired signals, making possible the comparison between the measures provided by conventional microphones. To carry out the psychoacoustic tests, the free field equalization must be removed so that the signals represent accurately the event. Likewise, the use of headphones during the detectability tests may affect the accuracy of the emitted signal with respect to the real sound. The frequency response of headphones can change the spectral content of the sample and thus, must be corrected. An inverse filter from the headphones impulse response was used to solve the aforementioned effects.

The background noise used in the auditory tests was obtained overlapping the noises emitted by several idling vehicles. The resulting signal presented an equivalent sound pressure level of 61 dBA.

2.4.2. Apparatus

Auditory tests were performed in a room with low level of noise. A software tool was implemented to perform the detectability test. The application emitted the stored sound samples randomly, over a constant and continuous background noise, by using an external sound card TASCAM US-144MKII. Background noise was present during

the whole test to avoid training effects. Sounds were presented to the listener binaurally using a high-quality reference class headphones AKG K612Pro. The level of each sample was previously checked using an acoustic dummy head (HeadAcoustics HSM III).

2.4.3. Procedure

An auditory test was carried out to determine the detectability of PTWs. The tests took place in a laboratory using headphones. The mopeds were presented to the listener in a pass-by mode, simulating the movement of the motorcycle in both directions. The two-wheeled vehicles approached the listener individually, at a constant speed around 20 km/h, covering a distance of ± 30 meters from the pedestrian. In order to increase the realism of the simulation, the motorcycles were presented under the background noise conditions described in the preceding paragraph. Samples were presented individually and randomly, and the time between sound events varied between 1 and 20 seconds. Each sound was played six times - three in the left-right direction and three in the opposite - making a total of 36 sound events by subject. Listeners must indicate, by pressing a button, the moment they perceived the vehicle approaching.

2.4.4. Participants

A total of thirty seven volunteers (18 women and 19 men), mostly university students, took part in the auditory experiment. Participants were aged between 16 and 70 years (mean and median ages of 25.1 and 20.0 years, respectively). All the subjects declare normal hearing and vision ability. Non of the participants was an expert in the topic. The test procedure was explained to all participants, describing in detail the road-crossing scenario and the task of detecting the approaching vehicle as soon as possible and pressing a key. Different sound samples of the motorcycles were presented to the listeners before the test began.

3. Results

3.1. Influence of the speed in the sound pressure level

The analysis of the sound pressure level emitted by the tested vehicles at diverse speeds showed a significant difference between electric and internal combustion motorcycles. The results highlighted a behaviour similar to that observed on four-wheeled vehicles [39]. As the vehicles speed increases, the noise generated by aerodynamics and tyre/road contact increases. At speeds above 50 km/h, the noise produced by these phenomena had a greater contribution than noise generated by propulsion system on the total sound emitted by the vehicle. Therefore, at high-speed regimes, the sound pressure level generated by an electric moped will be similar to that produced by an internal combustion model. Figure 2 shows the evolution of the sound pressure level for each PTW according to speed. Due to engine limitations, some vehicles did not reach speeds above 45 km/h. For the HEM running in electric

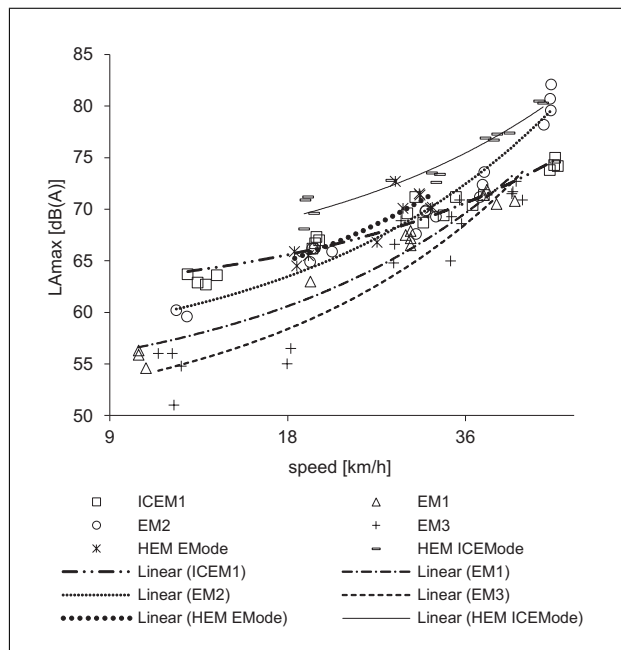


Figure 2. Sound Pressure Level against speed for the different PWTs. The lines represent the linear trend lines.

mode, the speed was limited at around 30 km/h by the control unit.

At speeds below 20 km/h the L_{Amax} emitted by the electric motorcycles was lower than that obtained for motorcycles with internal combustion propulsion system (ICEM1, $HEM_{ICEMode}$). Around 20 km/h, there was practically no difference in L_{Amax} between EM2, HEM_{EMode} and ICEM1 (1dBA). However, between ICEM1-EM1 and ICEM1-EM3, the difference in SPL was 4 and 8 dBA respectively. At 13 km/h, the difference in L_{Amax} for ICEM1 and EM3 was 9 dBA. At 40 km/h the difference was reduced to less than 1 dBA regarding ICEM1.

A spectrum analysis showed the appearance of harmonic frequencies in electric motorcycles (see Figure 3). This behaviour was observed for all electric motorcycles at speeds above 20 km/h. These tonal components were linked to the vehicle speed, changing their value as the velocity increases. The existence of tonal components may result in an increase of the annoyance perceived by drivers and pedestrians [40]. Clear harmonic frequencies were not found for motorcycles powered by internal combustion engines, ICEM1 and $HEM_{ICEMode}$ (see Figure 4).

3.2. Horizontal directivity

The global sound pressure level radiated for each PTW during the pass-by tests in the frequency range from 350 to 2800 Hz was analysed at around 20 km/h (see Figure 5). As already concluded in the previous section, the SPL generated by ICE motorcycles was generally higher than the levels obtained from EMs. Signals were analysed in terms of directivity at three different octave bands: 500 Hz, 1000 Hz and 2000 Hz. For motorcycles powered by internal combustion engines, ICEM1 and $HEM_{ICEMode}$, the directional effect of tyre-road noise was reduced due to the

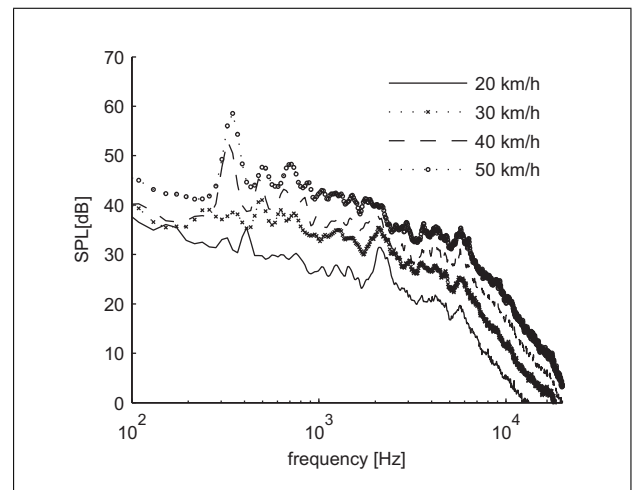


Figure 3. Evolution of the frequency spectrum with the speed for EM2.

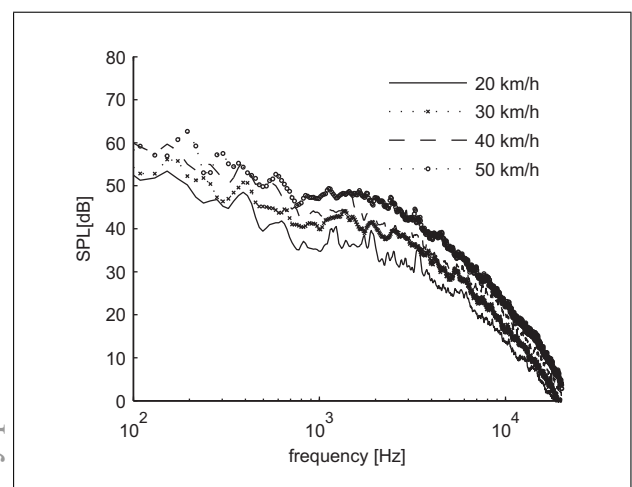


Figure 4. Evolution of the frequency spectrum with the speed for ICEM1.

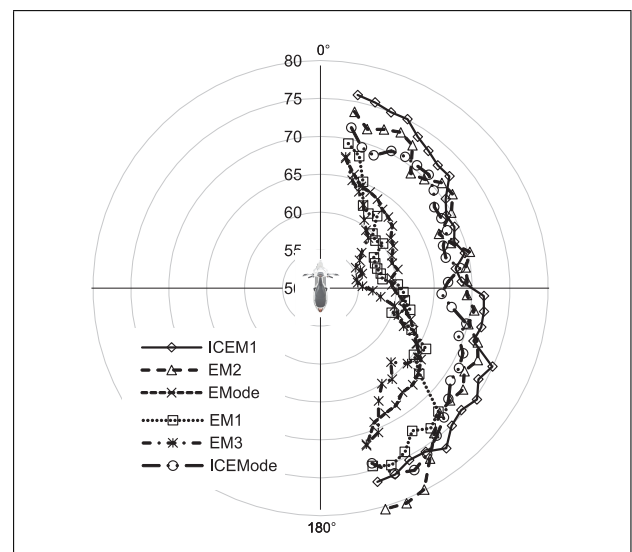


Figure 5. Global sound pressure level, in the frequency range from 350 to 2800 Hz, at around 20 km/h depending on the angle.

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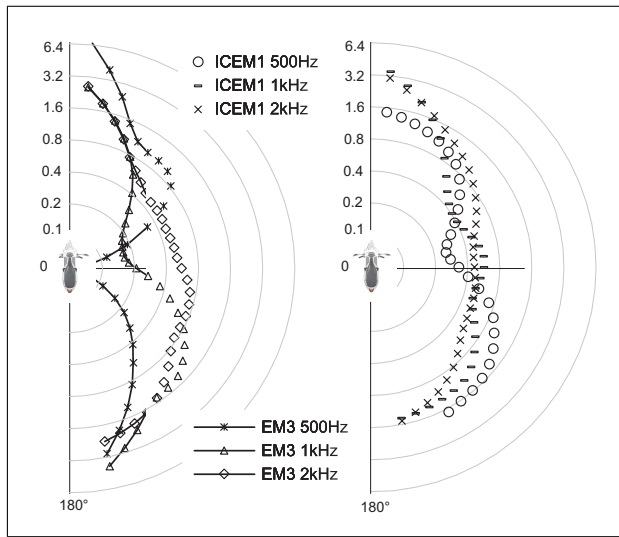


Figure 6. Directivity factor Q comparison between ICEM1 (right) and EM3 (left) at around 20 km/h. At low frequencies, the EMs analysed showed very similar directivity factor values for the front and rear of the vehicle, and lower on the central part (angle of 90°).

masking effect caused by the mechanical sound radiated by the engine.

The directivity factor Q , defined as the ratio between the square pressure in a certain angle and the average of the square pressures in all directions, was analysed. Figure 6 shows the Q values obtained for two tested motorcycles with different propulsion system, ICEM1 and EM3. At low frequencies, EM3 presented a radiation pattern significantly more directive than ICEM1. At high frequency bands, Q values obtained for both propulsion systems become more similar.

This behaviour resulted in more directive radiation patterns. On the contrary, horizontal directivity for motorcycles ICEM1 and HEM_{ICEMode}, both equipped with a combustion engine, showed a dissymmetry between the front and rear of the vehicle. This phenomenon was due to the exhaust pipe and similar results were found in [23]. The HEM used in this research was a clear example of this effect. HEM running in ICE mode had, for angles above 140° , a directivity factor higher than in electric mode (see Figure 7).

Figure 8 shows the maximum DI for EM3 for the angles from 0° to 90° (angular sector consider as the most sensitive for pedestrians), at speeds between 20 and 50 km/h, for 500, 1000 and 2000 Hz octave bands. The values of DI were obtained from the average of different iterations carried out during the pass-by test at the same speed. The results showed a progressively decrease of the directivity with the speed of the vehicle. The approximation of the data with a second-order polynomial function provided correlation values over 90%.

3.3. Auditory Detectability Test

3.3.1. Descriptive results

During the auditory test, each sound was played six times - three in the left-right direction and three in the opposite.

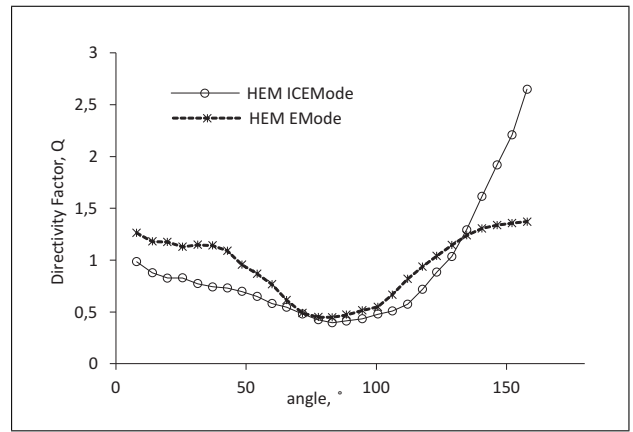


Figure 7. Directivity factor Q for the hybrid motorcycle at 20 km/h and 500 Hz octave band.

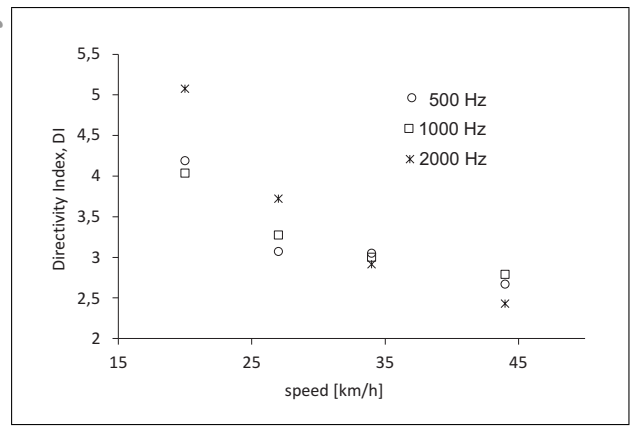


Figure 8. Directivity Index of EM3 at different speeds and octave bands. Maximum value, calculated for the angles from 0° to 90° .

In order to analyse data globally, the influence of the direction motion into the reaction time was studied. The results revealed that direction motion had no significant influence on the listener reaction time: $t(36) = 0.01$, $p = 0.99 > 0.05$. Data obtained in both directions were collapsed for subsequent analysis.

Some participants committed errors in the detection of some vehicles. At times, detections took place once the listener had been run over, which produced negative distances to pedestrian in the test results. Some other times, subjects did not press the corresponding key during the test, so the time value for the sample was lost. The two situations described above were considered errors and treated in the same manner. The percentage of errors on the total detections was 3.25%. Analysing vehicles depending on their propulsion system, detection errors represented 2.25% for ICEM and 3.60% for EM (see Figure 9). Data concerning errors committed depending on the type of propulsion system did not comply the requirements for a parametric analysis of variance (ANOVA) test. Levene's test indicated unequal variances ($F(1, 220) = 6.432$, $p = 0.012 < 0.05$). Also, Shapiro-Wilk test showed that errors did not follow a normal distribution ($W_{ICEM}(74) = 0.392$, $p < 0.05$; $W_{EM}(148) = 0.440$, $p < 0.05$). Non-

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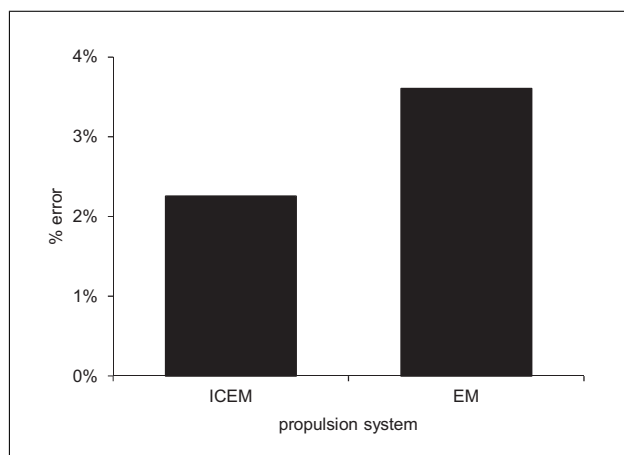


Figure 9. Detection errors depending on the propulsion system.

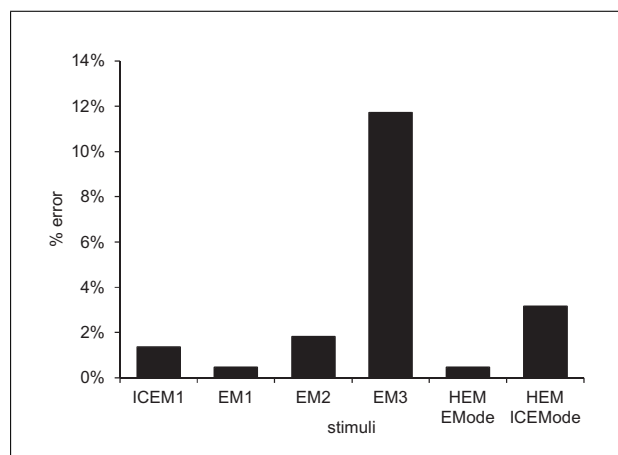


Figure 10. Detection errors depending on the PTW.

parametric method was used to determine the significance of propulsion system into the errors committed by subjects. Kruskal-Wallis H test showed that there was no statistically significant difference in detection errors between different propulsion systems, $\chi^2(1) = 0.782$, $p = 0.376 > 0.05$.

According to non-parametric Kruskal-Wallis H test, there was a statistically significant difference between all models, $\chi^2(5) = 45.456$, $p < 0.05$, analysing errors by motorcycles (see Figure 10). A pairwise comparison port-hoc test showed that there is statistically significant difference between EM3 and the remaining stimuli ($t_{1_4}(1) = -46.324$, $p_{adj} < 0.05$; $t_{2_4}(1) = -52.081$, $p_{adj} < 0.05$; $t_{3_4}(1) = -43.014$, $p_{adj} < 0.05$; $t_{5_4}(1) = 52.081$, $p_{adj} < 0.05$; $t_{6_4}(1) = 37.257$, $p_{adj} < 0.05$; where p_{adj} denotes p-values adjusted using Bonferroni method). Figure 10 shows the percentage of error for each PTW. Reaction times associated with erroneous detections were removed for further analysis.

Global reaction time represented a normal distribution with $M = 3.09$; $SD = 0.57$; $CV = 18\%$ (Figure 11).

Analysing the reaction times by motorcycle, a Levene's test indicated unequal variances ($F(5, 215) = 5.444$, $p < 0.05$). In the same way, data concerning reaction times by propulsion system presented unequal variances ($F(1,219) = 28.618$, $p < 0.05$). Data violated the assumptions of normality and homoscedasticity necessary to implement parametric analysis methods and therefore, results were statistically analysed by a non-parametric Kruskal-Wallis H test.

3.3.2. Influence of propulsion system in auditory reaction time

As indicated in paragraph 3.3.1., reaction times by propulsion system did not comply the requirements of normality and homoscedasticity needed to apply the parametric ANOVA test. In this case, non-parametric tools were used to study the relationship between propulsion system and the reaction time. The Kruskal-Wallis H test showed that there was a statistically significant difference in reaction time between propulsion systems, $\chi^2(1) = 121.848$, $p <$

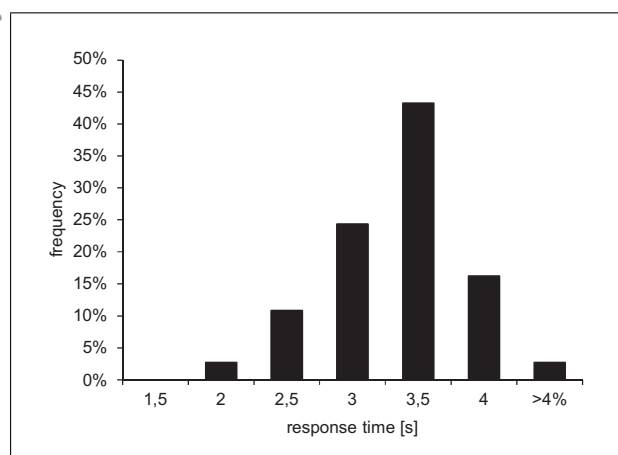


Figure 11. Distribution of mean overall reaction times of all subjects and vehicles.

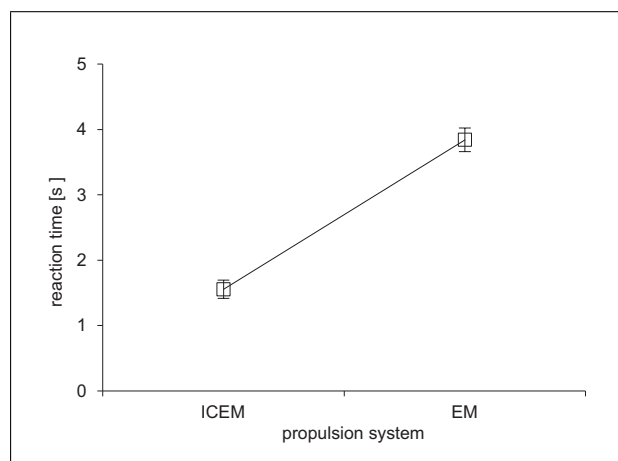


Figure 12. Mean reaction time depending on the propulsion system.

0.05. As shown in Figure 12, mean reaction time for EM was higher than ICEM one ($RT_{EM} = 3.84$ s; $RT_{ICEM} = 1.55$ s). Given the speed of motorcycles (19 ± 1 km/h), the difference supposed a spatial distance of 12 m.

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Table II. Statistical descriptors. Mean Reaction Times. Lower/Higher: Lower/Higher limit of the 95% confidence interval for the mean.

PTW	RT Mean	Lower	Higher
ICEM1	1.857	1.594	2.120
EM1	3.447	3.163	3.731
EM2	2.877	2.612	3.142
EM3	5.031	4.811	5.252
HEM _{EMode}	4.011	3.738	4.284
HEM _{ICEMode}	1.284	1.179	1.389

3.3.3. Differences between powered two wheelers

This section analyses the influence of the vehicles in the reaction time of the subject. Reaction times obtained for HEM_{ICEMode} presented a standard error significantly lower than other motorcycles. This resulted in a lower variance and a narrower 95% confidence interval for the mean (see Table II). Non-parametric methods were used to analyse the data.

The Kruskal-Wallis H test showed that there was a statistically significant difference in reaction time between motorcycles, $\chi^2(5) = 164.700$, $p < 0.05$. A pairwise comparison post-hoc test showed that there is no statistically significant difference between ranges for some motorcycles as show in Figure 13.

Figure 13 shows the mean reaction time obtained for each motorcycle. According to the statistic results, there was a significant difference between ICEMs (including HEM_{ICEMode}) and EMs. Motorcycles with electric propulsion system resulted in higher reaction times, which means a higher risk of crash for pedestrians. In accordance with the results obtained in Section 3.3.1., vehicle with higher reaction time lead to greatest number of detection errors.

Kruskal-Wallis H test showed that there was no significant difference between reaction times for the different groups of ages described in paragraph 3.3.1., $\chi^2(2) = 4.006$, $p = 0.135 > 0.05$.

The maximum difference in the reaction time between motorcycles was 3.74 s, which corresponded to a distance of 19.97 m (vehicle speed during the test of around 19 km/h). The minimum time difference between electric and internal combustion motorcycles was 1 second, which means a distance of 7 meters. Figure 14 shows the mean distance between PTW and pedestrian at the time of detection. Electric vehicles were detected at a shorter distances from the pedestrian. According to [25], at 19 km/h the stopping time for a motorcycle is 0.58 s, which represents a stopping distance of approximately 3 m. Considering the reaction time of the driver (0.75 s – 3.96 m), the total stopping distance for a motorcycle running at a speed of 19 km/h will be 7 m. This distance sets the safety limit for pedestrian since, although the driver detected his presence, he would not have time to stop the motorcycle. The safety limit will depend on driver attention, the road surface, the weather conditions and the condition of the vehicle at the time. Thus, moped EM3 represented a real risk for pedestrians. In this case, the PTW was detected at

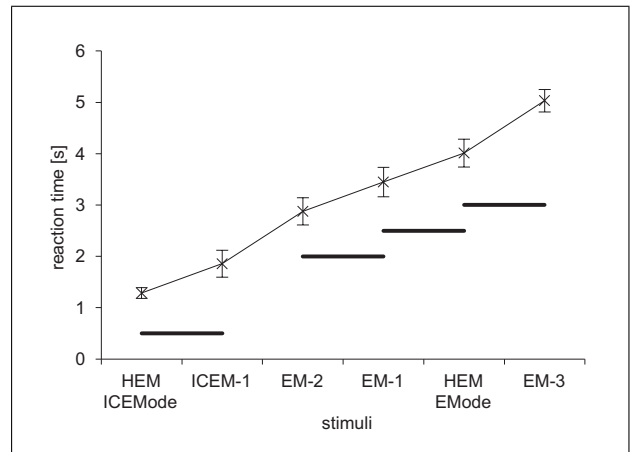


Figure 13. Mean reaction time depending on the PTW. Horizontal lines denote pairs with no statistically significant difference.

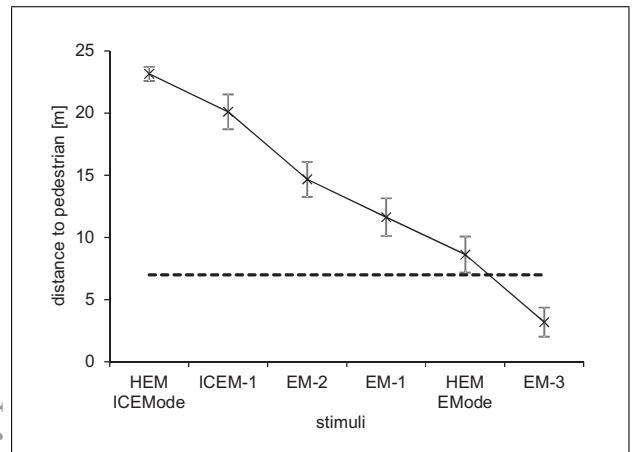


Figure 14. Distance in meters at which the observer detected the vehicle. Dotted line represents unsafe distance calculated as describe in paragraph 3.3.2.

a distance under the minimum safety distance ($RT_{EM3} = 5.03$ s; $DP_{EM3} = 3.18$ m). Similarly, the hybrid motorcycle running in electric mode was detected close to the limit – lower limit of 95% confidence interval for the mean equal to 7.17 m. An increase of the equivalent sound pressure level of the background noise used during the tests should result in an increase of the reaction times.

Analysing the temporal history of SPL for each motorcycle during the pass-by test, it is possible to establish a detection threshold at which the vehicles were detected by pedestrians. The comparison between the threshold obtained for all the motorcycles showed a maximum difference of 3.4 dBA:

$$ICEM1, 51.4 \text{ dBA}; \quad HEM_{EMode}, 54.8 \text{ dBA}.$$

Figure 15 highlights how the detection for both propulsion systems available on the hybrid motorcycle took place practically at the same level (difference less than 1 dBA). As evidenced in [10], the detection threshold will be significantly affected by the background noise.

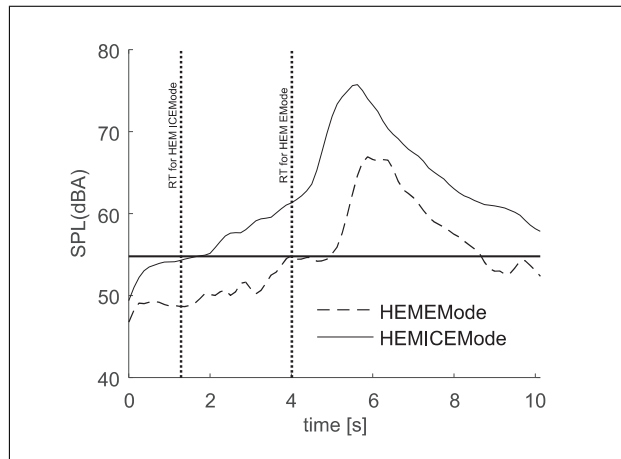


Figure 15. Time history of sound pressure level during the pass-by test for the hybrid motorcycle. The horizontal line denotes the detection threshold for both propulsion systems.

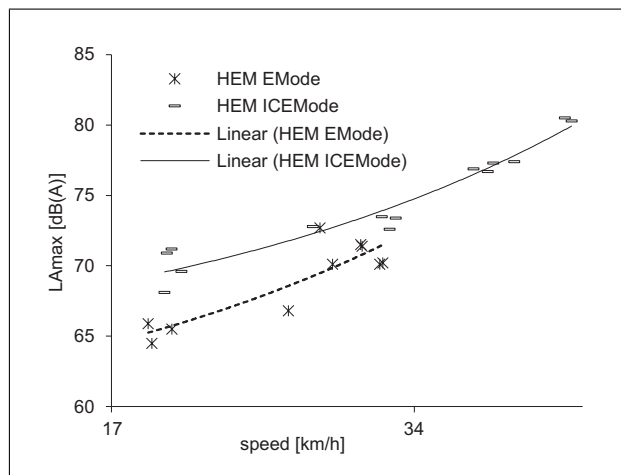


Figure 16. SPL depending on the speed for a hybrid motorcycle.

3.4. Hybrid electric powered two-wheelers

In order to compare different propulsion systems with the same boundary conditions, a hybrid electric motorcycle was studied. This kind of PTW allowed to activate or deactivate the electric mode by pressing a button. This facilitated to perform measurements in a certain speed range – 18 to 30 km/h – with both propulsion systems. Above 30 km/h, the motorcycle automatically switch off the electric engine and turn on the ICE mode.

Analysing the emitted noise of the PTW running in each mode, ICE mode presented a sound pressure level 7 dBA higher than the electric mode at 20 km/h (see Figure 16). The difference decreases as the speed increases, obtaining a gap of 4.5 dBA at 30 km/h. This behaviour was due to the fact that as the speed increases, the noise produced by the tyre-road contact and the aerodynamics of the motorcycle becomes more relevant in the overall noise. So, at higher speeds, the level of noise emitted by the motorcycles was equal for both propulsion systems.

The difference between both systems was reflected too in a detectability delay of approximately 2.7 s, which cor-

responds to a distance of about 14.5 m ($RT_{HEM_ICEMode} = 1.28$ s; $RT_{HEM_EMode} = 4.01$ s). The results confirmed how the propulsion system affects the vehicle detectability. The Kruskal-Wallis H test showed that there was a statistically significant difference between the reaction time for both propulsion systems, $\chi^2(1) = 53.515$, $p < 0.05$.

4. Discussion

The current study analyses the acoustic behaviour of powered two-wheelers with different propulsion systems and determine the risk for pedestrians on the approach of an electric PWT at 20 km/h. For this, a pass-by test was carried out on a total of 5 motorcycles. The sound pressure level and the horizontal directivity of each vehicle were analysed at different speeds. To analyse the detectability of motorcycles at 20 km/h, an auditory test was carried out in a laboratory. Sound samples used were obtained during the pass-by tests by means of an acoustic dummy head. Auditory tests were conducted on a total of 37 people, mostly students.

The results revealed a significant difference between the sound pressure level generated by the electric and internal combustion motorcycles at low speeds (approximately 9 dBA at 13 km/h) as in [23]. As the velocity of the vehicle increased, the difference between both propulsion systems was reduced (approximately 1 dBA at 40 km/h). At high speeds, the noise produced by aerodynamics and the tyre-road contact resulted more significant and hence, noise produced by all vehicles became equal. At the same time, the absence of mechanical engine noise for EMs resulted in a more directive radiation patterns. In the same way as [23], those motorcycles provided with internal combustion engine showed a dissymmetry in the horizontal directivity between the front and rear of the vehicle. This effect was mainly due to the exhaust pipe. On the other hand, the relationship between speed and directivity was studied. In accordance with the results, an increase in the speed carries to a decrease in the maximum directivity index of the motorcycle calculated for the angles from 0° to 90°.

The difference in level observed at low speed resulted in a decrease of the detectability for electric vehicles. Motorcycle EM3 was detected at a mean distance from the pedestrian of 3.18 m. This distance was less than the safety limit set by the stopping distance of the vehicles. The difference in the mean reaction time for internal combustion engine and electric motorcycles was 2.3 s (ICEM1 and EM2). Therefore, there is a real risk for pedestrians because of the incorporation of this kind of vehicles to the urban traffic. It should be noted that the difference between reaction times resulted for a hybrid moped in both operating modes (electric and internal combustion engine) was over 10 meters. Besides, it was observed a significant relationship between directivity and detectability for PTWs.

The temporal history of SPL during the pass-by test allowed to obtain a detection threshold for each motorcycle. A comparison of all of them revealed a maximum difference in the detection level of 3.4 dBA. For the hybrid mo-

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torcycle, the difference was less than 1 dBA between the two propulsion systems.

The results shown in this study were obtained under specific background noise conditions. The use of other surroundings, like the use of urban environment with higher levels of noise, should result in a decrease of reaction times and even could involve the non-detection of some of the tested vehicles. According to the results, the need of an alerting system in two-wheeled vehicles must be considered.

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