Research Article

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Electric vehicles diffusion: changing pavement acoustic design?

Abstract: Electric vehicles (EVs) are progressively entering into the current noisy urban ecosystem. Even though EVs are apparently quieter than traditional Internal Combustion Engine Vehicles (ICEVs), they have an impact on noise maps and road pavement designers should take this into consideration when designing future low-noise road pavements. Consequently, the main objective of this study is to define what are the most important aspects that road pavement designers should take into account. For this reason, in this paper, the noise emitted by EVs was analysed, considering parameters (*e.g.*, speed and frequency) and comparisons, in order to identify crucial characteristics. Results show that EV noise could call for the improvement of pavement acoustic design due to the Acoustic Vehicle Alerting System (AVAS), high-frequency peaks, and noise vibration harshness.

Keywords: Internal combustion engine vehicles, Electric vehicle, Traffic noise, Road pavement design

1 Introduction

We tend to think that Electric vehicles (EVs) are quite silent, but it was amply proved that electric motors can emit noise [1]. The advent of EVs into the current traffic-noise-related ecosystem can be compared to the introduction of a new species in a given ecosystem [2], which need to be studied considering different points of view, *i.e.*, of authorities, pedestrians, drivers, and designers. Hence, designers should consider the impact of EVs on noise maps (especially in urban contexts), and take this into consideration when designing future low-noise road pavements [3].

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The first outcome of the studies mentioned above refers to the "excessive quietness" of EVs, especially at low speeds, *e.g.*, Sound Pressure Levels lower than 56 dB @about 10 km/h, cf. also [4]. This may affect the safety of pedestrians, riders, and Internal Combustion Engine Vehicles (ICEVs) drivers [4–6]. In order to solve this problem, regulation and systems have been proposed as discussed in the following (see Section 1.3).

Another important aspect related to the noise produced by vehicles (including EVs) is the tire/road interaction. Hence, solutions related to tires and roads were proposed.

Focusing on tires designed for EVs, Ejsmont *et al.* (2015) [7] concluded that these special tires generate noise similar to general use tires, and that a small noise reduction can be possible if narrow tires with big outer diameter are used. In 2016, Pallas *et al.* (2016) and Czuka *et al.* (2016) [8, 9], within the FOREVER project, investigated the tire/road noise of EVs, and the "low-noise tires" concept (using one EV and nine different tire sets) concluding that:

1. The rolling noise of light EVs does not differ from the one of conventional vehicles.
2. Ecological tires (*i.e.*, which reduce consumption) and current tires for EVs do not reduce significantly the rolling noise.

Mohammadi and Ohadi (2021) [10] proposed a novel approach to design quiet tires, based on multi-objective minimization of generated noise. In this latter study, all the predominant mechanisms related to tire/road noise (texture impact, tread impact, air pumping, pipe resonance, Helmholtz resonance, air cavity resonance, and horn effect) were included in the model. On average, this allowed reducing of about 2 dB(A) the total noise (corresponding to 80% reduction of the normalized texture impact noise), and of 27% the average normalized sound of a patterned tire, by modifying of about the 10% its structural and tread pattern parameters.

For quiet asphalt pavements, it is important to point out that their sound absorption can be modelled [11, 12] and measured using in-lab and on-site methods [13]. Furthermore, road sound absorption is related to several parameters (*i.e.*, thickness, porosity, air flow resistivity, and tortuosity), and more attention should be paid on the im-

portance of some of the aforementioned parameters (*e.g.*, air flow resistivity and tortuosity; cf. [14]) both for design and noise assessment.

Ling *et al.* (2020) [15] focused on the appreciable noise performance of the following pavement technologies 1) Porous asphalt pavement (PAP, *i.e.* asphalt concrete mixtures with typical air void content, AV, of 15–20% and noise reduction of 3–6 dB in comparison with traditional asphalt pavements). 2) Rubber asphalt pavements. This solution contains 3–5% of crumb rubber from tires (added applying the dry or wet process, including terminal blend rubber modified asphalt), with a vibration attenuation of 20–25%, and a noise reduction of 1–5 dB in comparison with ordinary roads. 3) Ultra-thin wearing courses, UTWC, *i.e.*, asphalt concrete mixtures with thickness of 2-3 cm, which can contain fibers or rubber chips, and can allow vibration and noise reduction. 4) Porous elastic road surface, PERS, *i.e.*, asphalt concretes that contain crumb rubber (at least 20% of the total mix volume) and usually polyurethane resins, with a porosity higher than 20%. This allows noise reductions of 6–12 dB in comparison with ordinary roads. 5) Stone mastic asphalt pavements, SMAP, *i.e.*, asphalt concrete mixtures characterized by gap-graded dense skeleton with voids, AV, of 3–8%, filled with a high percentages of asphalt binder, stabilizer and finer aggregate, and with a variable Nominal Maximum Aggregate Size, NMAS. The factors above affect surface texture, allowing tire-road noise mitigations at low, medium and high frequencies.

Nevertheless, traffic conditions, noise reduction requirements, and local climatic conditions must be taken into account to select the best low-noise wearing course. Praticò *et al.* (2020) [16] proposed an experimental method to design porous asphalts to account for surface and volumetric properties (*e.g.*, acoustic absorption, drainability, texture, and friction), which are linked to intrinsic factors (*e.g.*, gradation and bitumen content) and extrinsic factors (*e.g.*, traffic load), and which decay over time (reduction of friction and high-frequency acoustic absorption). Vázquez *et al.* (2020) [17] found that road pavements with lower dynamic stiffness reduce the sound power and noise levels at high frequencies. Chen *et al.* (2021) [18] studied the influence of pavement characteristics (*i.e.*, macrotexture and porosity), tire type and load, driving speed, CPX trailer weight, and air temperature on tire/pavement noise. A Bayesian model was proposed, and it was observed that tire/pavement noise level 1) Mainly depends on driving speed. 2) Increases with macrotexture depth. 3) Decreases with surface porosity. 4) Is attenuated by porous pavements, especially for higher driving speeds. 5) Increases when tire load increases. 6) Decreases as the air temperature increases.

Tire-road noise for EVs is the main topic of the ongoing LIFE project "E-VIA" (2019–2023) [19–24]. In more detail, the E-VIA project aims at 1) Considering the contribution (*i.e.*, both the noise and air pollution mitigation efficiency) of EVs and hybrid vehicles with respect to the current scenarios. 2) Optimizing both road pavements and tires (durability and sustainability) for EVs (that in turn reduce the Life Cycle Cost with respect to actual best practices). 3) Contributing to the effective implementation of to EU legislation (EU Directives 2002/49/EC [25], and 2015/996/EC [26], and CNOSSOS-EU [27]). 4) Raising people's awareness of noise pollution and health effects.

Another noteworthy example of EVs-related projects that aim at proposing strategies, guidelines and policy to accelerate EVs adoption is the Interregeurope project "E-MOPOLI" (cf. [28] and [29]).

By referring to the prediction of the effect of EVs and Hybrid EVs (HEVs) diffusion on urban noise maps, different studies were carried out [30–34]. In more detail, by referring to urban areas and to high percentages of of EVs (*e.g.*, after 2030), Verheijen and Jabben (2010) [33] estimated that:

– If fleets consisting of HEVs will be used, the average noise levels could be reduced of approximately 2 dB (with a reduction of annoyance effects of 20%).
– If fleets consisting of EVs will be used the average noise levels could be reduced of about 3–4 dB (with a reduction of annoyance effects of 30%).

Another example of estimation is the study of Jabben *et al.* (2012) [34]. They compared the noise produced *in situ* (urban conditions) by ICEVs and HEVs running on traditional or low-noise pavements. They estimated that the application of quiet solutions, such as silent tires and silent pavements, is going to reduce the current overall traffic noise level in urban context of 1.5–2 dB. Finally, Laib *et al.* (2019) [35] found that electric buses do not allow noise reduction on heavily trafficked roads, but, in a quiet residential area, the expected average noise reduction is about 5 dB(A), and good results (*e.g.*, a traffic noise reduction of 1 dB(A)) can be obtained on roads highly trafficked by bus (if they are the only heavy vehicles), where speeds are lower than 50 km/h, and close to the bus stops.

1.1 Objectives and tasks

Because of EV diffusion and the consequences above, the main objective of the study described in this paper is to assess the most important aspects that designers should take into account during the design of future road pavements

because of the progressive diffusion of electric vehicles in the current vehicle fleets, especially in urban contexts.

Figure 1 presents the logical process (*i.e.*, a sequence of causes and effects) that allowed generating the current study. In more detail, the diffusion of the EVs (cause) will impact the spectrum of the traffic noise (effect). Subsequently, new road pavements are needed in the future (cause), where designers should take into account the modification of the traffic noise mentioned above (effect).
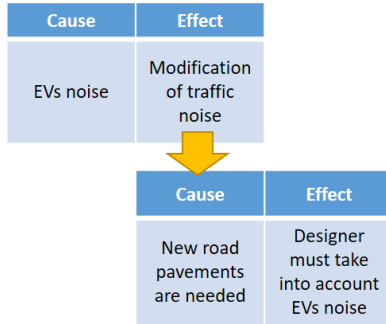

Cause	Effect
EVs noise	Modification of traffic noise

Cause	Effect
New road pavements are needed	Designer must take into account EVs noise

Figure 1: Subject presentation

In order to achieve the objectives above, the following tasks were carried out:

– Task 1. Analysis of the literature-1 (noise-speed relation).
– Task 2. Analysis of the literature-2 (differences in noise spectrum).

Based on the above, the remaining part of the paper is organized as follows: Sections 1.2 and 1.3 refer to Task 1 and 2, Section 2 describes the conclusions, and is followed by the references.

1.2 Analysis of the literature: noise-speed relation (Task 1)

Several studies have been carried out to measure the noise produced by EVs. This latter depends on the speed of the vehicles. Different standards were applied to measure the noise produced by moving vehicles through roadside experiments [36, 37], including:
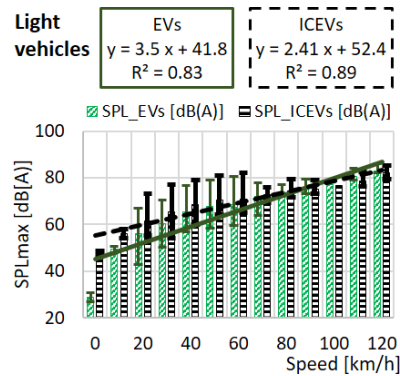
– ISO 11819-1 (1997) [38, 39]: this standard defines the Statistical Pass-By (SPB) method. This method is applicable to traffic travelling at constant speed, *i.e.* free-flowing conditions at posted speeds of 50 km/h and upwards and allows measuring the influence of road surfaces on traffic noise. Note that the controlled pass-by method, CPB, is a modified version of

the SPB method that may be carried out using either a single vehicle or selected vehicles (specified speed, specified gear).
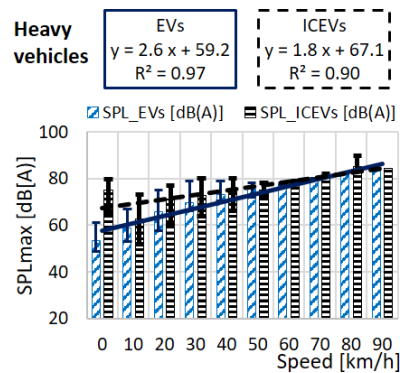– ISO 13325 standard (2019) [40], which deals with the Coast-by method that allows measuring the tire/road noise while the vehicle is in free-rolling (*i.e.*, non-powered operation, engine switched off).
– ISO 362-1 (2015) [41]: this method can be used considering accelerating vehicles (wide-open throttle test).

Usually, the maximum Sound Pressure Level (SPLmax) is derived using the methods defined above, and this parameter is used to compare the noise produced by EVs to that produced by the traditional Internal Combustion Engine Vehicles (ICEVs).

Figure 2 illustrates SPLmax as a function of vehicle speed and provides an overview about the comparison mentioned above, considering several studies [1, 8, 31, 32, 35, 37, 42–46], several methods (defined above), light and heavy electric vehicles (EVs), hybrid vehicles (HEVs), and ICEVs. Note that, in this case, the noise related to HEVs refers to the electric mode only.

Light vehicles	EVs	ICEVs
	$y = 3.5\,x + 41.8$	$y = 2.41\,x + 52.4$
	$R^2 = 0.83$	$R^2 = 0.89$

(a)

Heavy vehicles	EVs	ICEVs
	$y = 2.6\,x + 59.2$	$y = 1.8\,x + 67.1$
	$R^2 = 0.97$	$R^2 = 0.90$

(b)

Figure 2: Relation between noise and speed for (a) light and (b) heavy vehicles (EVs, HEVs, ICEVs) based on [1, 8, 31, 32, 35, 37, 42–46].

Based on the results reported in Figure 2, it is possible to state that:

– The maximum of the Sound Pressure Level (SPLmax) related to light EVs ranges from about 30 dB(A) to about 80 dB(A) when the speed of these vehicles goes from 0 to 120 km/h, while light ICEVs have SPLmax in the range 50–80 dB(A) in the same speed range mentioned above. Linear regressions seem to provide a good fit of the observations (quite good R^2 values were derived) and the equations are shown by Figure 2a. Great variations can be observed in the speed range 20–60 km/h.

– The SPLmax related to heavy EVs goes from about 50 dB(A) to about 80 dB(A) when the speed of these vehicles varies from 0 km/h to 90 km/h, while heavy ICEVs show values of SPLmax that vary in the range 60–80 dB(A), with a peak at 0 km/h (*i.e.*, due only to the engine of these heavy vehicles). Linear regressions provide a good fit of the observations (R^2=0.90–0.97; see Figure 2b), and moderate variations can be observed for speed lower than 50 km/h.

– Both light and heavy electric-powered vehicles (*i.e.*, EVs and HEVs) are more silent than ICEVs in the range 0–70 km/h (about 5 dB(A) on average).

– The higher the speed the lower the differences above. An opposite result may be observed for speeds higher than 90 km/h (0.5 dB(A) on average). These results confirm the results of other studies (*e.g.*, [31]).

Note that many studies paid attention to the noise produced by light vehicles moving at speeds in the range 20–60 km/h and this could affect data variability.

Additional details about the relation noise-speed, which were derived from the literature, are reported in the following.

During the COMPETT project (2012–2015) [1, 31, 32], a literature review about the noise from EVs was carried out. This review showed that:

– The propulsion noise (ICEV) is dominant at low speed (lower than 35 km/h), but at higher speeds the tire/road noise is dominant. Hence, in the urban context, the propulsion noise greatly contributes to the total traffic noise, and it is expected that the use of EVs (that are quieter than ICEVs at low speeds) will contribute to urban traffic noise mitigation.

– The main parameters that affect traffic noise are type of vehicle, speed, type of tires, type of road pavement, and microphone position.

In more detail:

1. At low speeds (25–50 km/h), the noise from EVs is lower than that produced by ICEVs (*i.e.*, max reduction of 1–15 dB for speeds in the range 8–30 km/h measured using microphones placed at 2–7.5 m from the cars and at heights in the range 1.2–2 m from the ground).

2. When considering the maximum noise level measured with a fast time weighting (LAFmax, dB, measured applying the pass-by method) for vehicles moving at speeds in the range 25–80km/h on an asphalt concretes with NMAS of 11mm (AC11), ICEVs are always noisier that EVs (*i.e.*, about 59–76 dB versus about 57–72 dB).

3. The comparison between the noise levels (dB(A), measured using the CPB [32]), for the same vehicle (Citroën Berlingo), equipped with an ICE and an electric engine, showed that for speeds lower than 30 km/h the ICE is noisier than the electric one, while the opposite result was obtained for higher speeds 30–60 km/h).

4. The comparison between the noise levels, (dB(A), measured using the CPB method) of an EV (Nissan Leaf) and that of an ICE car (VW Golf Variant), driven in the range 10–60 km/h, showed that the ICE car was always noisier (about 1 dB(A) on average) than the EV [1, 31, 32].

Pallas *et al.* (2015, and 2016) [8, 44], within the project "FOREVER" (2013–2014), measured the noise produced by a small electric passenger car, a larger hybrid passenger car, and an electric truck. They found a difference of 4.5 dB(A) between the quietest and the noisiest vehicle at any speed in the range 20–50 km/h. In more detail, they measured the maximum sound pressure level (SPLmax; dB(A)) at 7.5 m from an EV (Citroen C-Zero) driven at constant speeds in the range 10–100 km/h. Furthermore, they found that the CNOSSOS-EU model (which is designed for the estimation of ICEVs noise emission in octave bands in the range 63 Hz–8kHz; cf. [27]) overestimates the EVs noise (both propulsion noise component at speeds lower than 30 km/h and sometimes up to 50–60 km/h, and the rolling noise component) in most octave bands. Finally, they found that at low speeds (*e.g.*, urban context, road sections with limited speed, traffic congestion on interurban or national networks) and for short source-receiver distances (*i.e.*, at roadside), EVs allow reducing the traffic noise because of the fact that (unlike ICEVS) their engine noise is lower than rolling noise. Nevertheless, at low speeds, the propulsion noise of all the vehicles greatly affects the total noise in the lower frequency bands (and the corresponding sound waves propagate over

long distances). For these reasons, in order to increase the noise reduction, they recommended to use quieter dense road surfaces and porous road surfaces.

Subsequently, Ibarra *et al.* (2017) [47] studied the noise emitted by alternative fuel vehicles (*i.e.*, HEVs and EVs), for both near (microphone 0.2 m above the ground behind the vehicle) and far fields (microphone 7.5 m far from the vehicle at a height of 1.2 m – SPB method using backing board, ISO 11819-4), using an on-board measurement system based on two microphones (one located inside the engine hood and the other close to one of the wheels). They found that:

1. HEVs and EVs lead to a reduction of the suburban and urban engine noise of about 10 dB(A) compared to ICEVs (*i.e.*, diesel or petrol vehicles).
2. HEVs are noisier that EVs (3 dB(A) in suburban roads, and 7 dB(A) in urban roads), considering the engine noise, while HEVs emit the same tire-road noise of EVs (in both the scenarios).
3. The reduction of noise related to EVs and HEVs is negligible in suburban contexts, where high speeds are allowed and, for this reason, tire-road noise is the main source of noise.

1.3 Analysis of the literature (Task 2)

1.3.1 Differences in noise spectrum

Details about the relation noise-frequency are reported in the following.

During the aforementioned COMPETT project (2012–2015) [1, 31, 32], the following observations were made:

1. By comparing A-weighted frequency spectra of ICEVs and an EVs (cf. Figures 3b and 4b), driven at 40 km/h (microphone at 7.5 m from the vehicles, placed 1.2 m from the ground), absolute maxima for both ICEVs and EVs can be observed around 1 kHz, while only the ICE cars show supplementary peaks in the range 60–200 Hz. Note that the difference mentioned above is less relevant at 70 km/h. In both the cases (50 and 70 km/h), ICEVs are noisier (ΔSPLmax = about 27 dB) than EVs for the frequency range under consideration (20 Hz–6 kHz). It is important to underline that these differences in terms of frequency are clearly perceived by human ears.
2. By comparing the SPL of two electric "city cars" (Fiat 500 and Citroen C-zero, cf. Figures 4a and 4b), driven at 10 and 55 km/h (measured using the pass-by method and microphones 7.5 m far from the cars and 1.2 m above the ground), absolute maxima were ob-

served at about 1 kHz at 55 km/h, while additional peaks at about 250 Hz were observed at 10 km/h.
3. By comparing the A-weighted 1/3 octave band spectra for noise levels measured at about 10 km/h and at about 60 km/h (cf. solid lines in Figures 3c and 4c), light ICE- and EV-related spectra appear to have similar shapes but different amplitudes (ΔCPB max = 30 dB(A)). Again, at 60 km/h, additional peaks can be seen in the range 30–60 Hz for ICE cars. These latter results are quite similar for decelerating cars, while during the acceleration (*i.e.* 0.7–4.8 m/s^2), ICEVs are noisier than EVs (65–75 dB(A) compared to 57–72 dB(A)) and the spectra show additional peaks for ICEVs in the range 50-150 Hz.

Pallas *et al.* (2015, and 2016) [8, 44], within the project "FOREVER" (2013–2014) cited above, found that, for EVs, the SPLmax increases with the logarithm of the speed with a linear trend. A different trend was observed for low frequencies (63–250 Hz). They concluded that rolling noise and propulsion noise cannot be easily separated through the pass-by measurement approach and that some driving situations seem to reduce the acoustical benefit of EVs and HEVs. Consequently, they found that strong accelerations significantly increase the global A-weighted SPLmax in the frequency bands over 500 Hz, while braking (probably because of the energy recovery system) increases the same parameter in all the frequency bands below 30–40 km/h.

As mentioned above, Ibarra *et al.* (2017) [47] studied the noise emitted by HEVs and EVs in the near and far field. Results related to the near field noise showed that the engine hood of the car used in the study reduces the engine noise of about 5–10 dB in the range 20–500 Hz, and of about 25–35 dB in the range 500 Hz-20 kHz for HEVs and EVs. At the same time, results related to the far field noise showed that the air attenuation of the noise was irrelevant, while additive (about +6 dB, frequencies lower than 1kHz) and subtractive effects (in the range −2 dB−(+12 dB) for 3–6 kHz) are expected because of ground attenuation.

Furthermore, Ibarra *et al.* (2017) [47] applied the ISO 11819-4 on one HEV (Toyota Prius Hybrid) and one EV (Nissan Leaf Electric), for semi-dense asphalt (air flow resistivity of 9700–1200 kNs/m^4), and derived four average frequency power spectra (two for the HEV, and two for the EV) related to engine noise and tire-road noise. The engine noise-related spectra of both vehicles started from about 39 dB(A), had absolute maxima of about 65–70 dB(A) in the range 0.3–1 kHz, and had several spikes (between 40–60 dB(A)) at high frequencies (3–20 kHz) that are not present in the ICEVs-related spectra. In contrast, the tire-road-noise-related spectra of both vehicles started at about 45–50

dB(A), had absolute maxima of about 80 dB(A) around 1 kHz, and did not have spikes above 1 kHz.

Finally, they estimated (using the Attenborough *et al.* (2006) propagation model [48]) the level of the engine noise and the tire-road noise (power spectrum, dB(A), *versus* frequency in 1/3 octave band between 20 Hz and 16 kHz) generated by the vehicles mentioned above driven in suburban and urban conditions (far field). The two noise-related spectra and the two tire-road-noise-related spectra had a similar shape. They start at about 25–28 dB(A), and 15–18 dB(A), respectively. Both had absolute maxima at 1 kHz that the authors associated to the tire-road interaction. They showed spikes at 4 kHz, and 3 kHz, respectively, and also at about 15 kHz.

During the "CityHursh" project (2010–2012) [37, 49], the noise emitted by three EVs (Mitsubishi iMiev, Citroen C-Zero and Peugeot iOn) and two HEVS (Toyota Prius and FIAT 500 EVadapt) was measured according to the ISO 362-1:2007 standard. The overall spectra (SPL *versus* frequency) related to constant speed test (cars driven at constant speeds in the range 10-55 km/h to derive the tire-road noise) and wide-open throttle test (accelerating cars with a start speed of 50 km/h) were derived. The results of the constant speed test mentioned above showed that:

1. HEVs-related spectra span from about 10–30 dB(A) (at 10 km/h) to about 60–65 dB(A) (at 55 km/h), and have absolute maxima at about 1–1.25 kHz.
2. EVs-related spectra grow from about 10–25 dB(A) (at 10 km/h) to about 55–58 dB(A) (at 55 km/h), have absolute maxima at about 1–1.25 kHz and then decrease.
3. The tire-road noise produced by HEVs is greater than that of the EVs (from 35–40 dB(A) to 67 dB(A) and from 33 dB(A) to 60–62 dB(A), respectively, for speeds in the range 10–55 km/h).

The company SIEMENS (2017) [50] studied the vibro-acoustic engineering challenges (in terms of frequency ranges of interest related to vehicle speeds) in ICEVs, HEVs and EVs (cf. Figure 8). In more detail, for ICEVs, the frequency ranges of interest are as follows:

- @speeds<60 km/h, engine-structure noise (20–400 Hz) and the engine-air noise (400 Hz–8 kHz).
- @60–100 km/h, tire-road noise (20 Hz–2 kHz),
- @speeds>100 km/h, wind noise (*i.e.*, aerodynamic noise) for 250 Hz–8 kHz.

On the other hand, for EVs:

- @speeds<40 km/h, the Heating, Ventilation and Air Conditioning (HVAC) and ancillary noise (20–200 Hz).

- @40–100 km/h, the electric engine noise (200 Hz–1 kHz), the inverter noise (1–8 kHz), and the tire-road noise (20 Hz–2 kHz).
- @speeds>60 km/h: wind noise (*i.e.*, aerodynamic noise), for 250 Hz–8 kHz.

In addition, in the same study cited above [50], it was found that EVs and HEVs have a quite specific Noise Vibration Harshness, NVH, behaviour (where it is noted that harshness is a subjective quality that mainly refers to psychoacoustics). Unpleasant or excessive sounds and vibrations inside a vehicle (*e.g.*, due to aerodynamic effects, or to the cooling pump, etc.) negatively affect both the driving experience and the perception of the vehicle quality (but also fuel consumption, passenger comfort, and drivability). Because of low-emission and zero-emission regulations, the interest for the NVH-related comfort (at component, subsystem, and full-vehicle levels) is increasing (see also [51]), and the automotive sector is studying how to balance vehicle-related parameters such as cost, efficiency, weight, and performance. These studies suggest a wide spectrum of considerations about pitch, timber, loudness, and duration, such as:

- EV low-frequency interior noise can be reduced acting on the vehicle mass during the structural design, *i.e.*, by reducing steel sheet thickness and using vibration damping steel.
- EV high-frequency tonal components can be reduced by increasing the isolation and absorption of the vehicle sound package components.

Lan *et al.* (2018) [45] carried out a study on the noise emission of light and heavy EVs on urban roads in China in order to define an emission model (based on measured data) and compare frequency spectra of EVs and ICEVs. They found that:

1. On average, the SPL (@16Hz–16kHz and @22–67 km/h) of EVs is lower (of about 5.5 dB(A), *i.e.*, 2.8 dB(A) for light EVs, and 8.2 dB(a) for heavy EVs) than that of ICEVs.
2. Light EV- and ICEV-related spectra grow from 10 Hz to 1kHz (0–55 dB(A)), have absolute maxima around 1 kHz and then decrease, and only the EV-related spectrum has a second peak at about 5 kHz.
3. The heavy ICEV-related spectrum grows quickly from 10 Hz to 60 Hz (0–65 dB(A)), is almost constant until 3 kHz and then decreases, while the EV-related spectra grow slowly from 10 Hz to 2 kHz, has the absolute maximum around 2 kHz and then decrease.
4. The noise energy (frequency content) of EVs is more concentrated than that of ICEs (*i.e.*, for light EVs is

within the range 500 Hz–1.6 kHz, while for heavy EVs is within 630 Hz and 2.5 kHz).

5. Based on measured data, the equivalent frequency (*i.e.*, the frequency, selected among all the center frequencies of 1/3 bands between 350 Hz and 2500 Hz, that is more often associated to the maximum A-weighted sound pressure level) of light EVs and light ICEVs is 1000 Hz and 800 Hz, respectively. While the same parameter for heavy EVs and heavy ICEVs is 1000 Hz and 630 Hz, respectively.

6. Simulations showed that if the percentage of EVs increases of 10%, the noise of the traffic flow decreases of 7 dB(A).

The following figures (Figures 3-5) show several noise spectra related to both light and heavy ICEVs and EVs [31, 32, 37, 45, 52]. In particular, these figures report the A-weighted Sound Pressure Level of:

1. ICEVs (see Figure 3) and EVs (see Figure 4), moving at different speeds (9–70 km/h), measured applying the Statistical Pass-By method (ISO 11819-1:1997).
2. EVs (see Figure 5) moving at constant speeds, derived applying the method described in the ISO 362-1-1:2015.
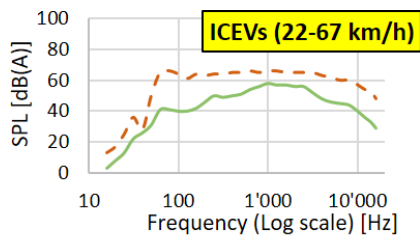
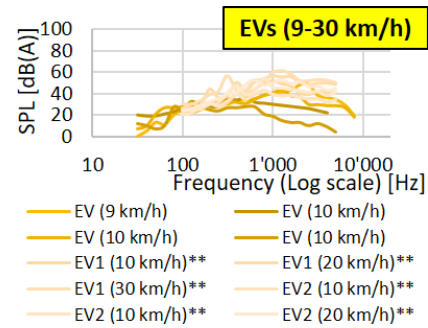Note that the measurements related to heavy vehicles were pointed out by using asterisks.
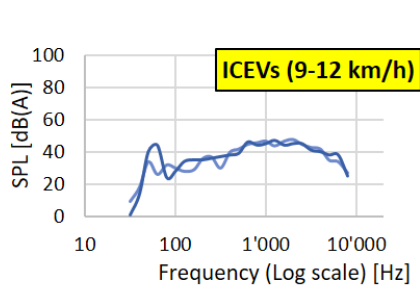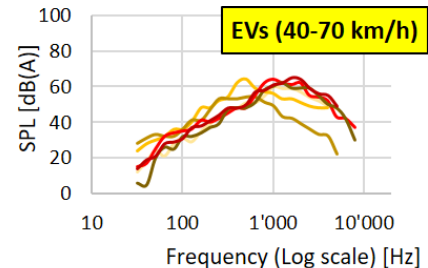

(a) [31]
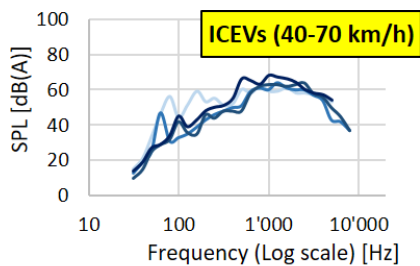
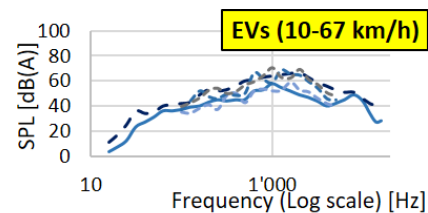**(b)** [31, 32]

(c) [46]

Figure 3: A-weighted Sound Pressure Level (Statistical Pass-By method, ISO 11819-1:1997) of ICEVs at different speeds (* = heavy vehicle) [31, 32, 45].

(a) [31, 32, 52]

(b) [31, 32]

(c) [46, 52]

Figure 4: A-weighted Sound Pressure Level (Statistical Pass-By method, ISO 11819-1:1997) of EVs at different speeds (* = heavy vehicle; ** = motorcycle) [31, 32, 45, 52].
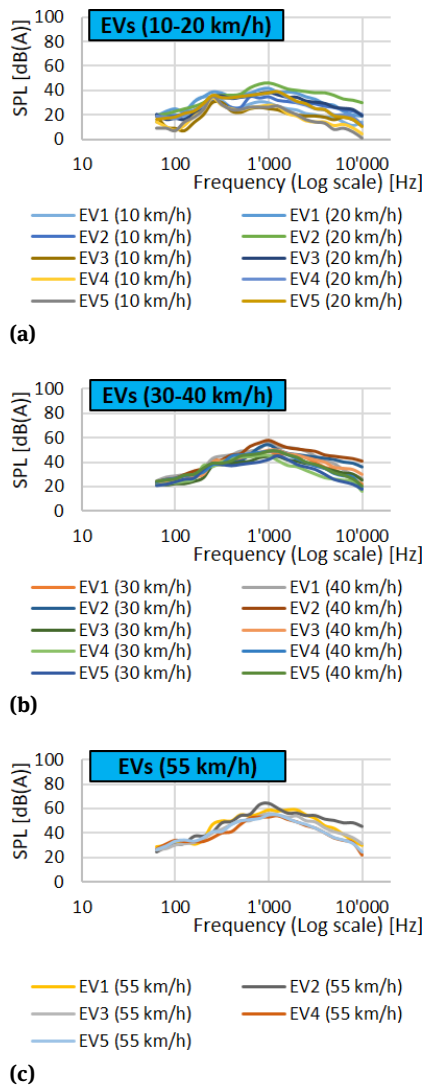
Figure 5: A-weighted Sound Pressure Level (ISO 362-1-1:2015) of five different EVs at constant speeds [37].

Based on the spectra in Figures 3–5, it is possible to state that:

– SPLmax (for speeds that vary in the range 9-70 km/h) of ICEVs is in the range 47-82 dB(A) and is usually located in the frequency range 800-2500 Hz (cf. Figure 3). For EVs, the spectrum peaks range from 30 to 65 dB(A), at 125-2000 Hz (cf. Figures 4 and 5). Importantly, ICEVs show a peak at about 50-160 Hz that is not present in the spectra related to EVs.
– In general, the higher the speed is the higher the peak frequency is, the higher the SPL is *per* given frequency.

1.3.2 Acoustic Vehicle Alerting System (AVAS)

The absence of exterior sounds or "quietness" of HEVs and EVs (especially at low speeds, *i.e.*, below 20 km/h, where the tire/road noise contribution is very low) can affect pedestrian and riders' safety [5, 53–56].

For this reason, quiet vehicles must be equipped with an Acoustic Vehicle Alerting System (AVAS) that allows reproducing a pleasant continuous sound (for people inside and outside the quite vehicles), for example, similar to those produced by ICEVs but quieter, while they are moving at low speeds (up to 20-30 km/h), and must allow pedestrians to identify constant driving speed, acceleration, deceleration, and in reverse [5].

To this end, the following examples of standards and regulations have been enacted [5, 42, 57–59]:

1. ISO 16254 (2016; to define electric vehicle warning sounds).
2. SAE J2889-16 (2011; about the minimum noise emitted by road vehicles).
3. Guideline of the Ministry of Land Infrastructures Transport and Tourism of Japan (2011).
4. United Nations Economic Commission for Europe (UN ECE) Regulation 138 (mandatory since 2019).
5. GB/T 37153-2018 (Chinese standard to define the electrical car low speed tone; mandatory since 2019).
6. United States Federal Motor Vehicle Safety Standards (US FMVSS) 141 (mandatory since 2020).
7. Norwegian Directorate for Children, Youth and Family Affairs (2019).

The UN ECE regulation [55] defines the minimum sound level that must be produced by the AVAS for vehicles driven at 10 and 20 km/h in the forward direction (SPLmax of 50 and 56 dB(A), respectively), while 47 dB(A) is the threshold for the reverse direction). AVAS minimum sound levels refer to two constant speeds, *i.e.*, 10 and 20 km/h. For each frequency (in the range 160–5000 Hz, $1/3^{rd}$ octave bands) and speed (10 or 20 km/h), a minimum sound level in dB(A) is requested.

At the same time, the US standard (FMVSS regulation N.141) requires the use of the AVAS sound at 30 km/h [60, 61].

The effects of AVAS sound (emitted from different EVs and measured applying the SPB method by Sakamoto *el al.* 2012 [62]) on noise spectra seem more evident at 10 km/h (about 1–11 dB(A) in the ranges 800 Hz–2 kHz, and 2.5–10 kHz. AVAS effect seems less relevant at speeds greater than 20 km/h (1–6 dB(A) above 2 kHz).

Fleury *et al.* (2016) [53] investigated three types of external AVAS sound. They concluded that:

1. Frequency modulations and pitch increase (*e.g.*, trying to intensify the high frequencies, which are more detectable than low frequencies in urban contexts) are crucial factors in AVAS sound design to increase the EV detectability.

2. Vehicle speed variations (*e.g.*, acceleration) need to be followed by AVAS sound fluctuations because of the fact that several studies demonstrate that blindfolded pedestrians have problems to recognize nature of the sound and vehicle speed (*i.e.*, underestimate speeds greater than 45 km/h, and overestimate speeds lower than 35 km/h). In more detail, it was observed that at 10 km/h pedestrians overestimate vehicle speeds, and the phenomenon is more relevant when pitched AVAS sounds are used (when the pitch was lightly varied, the vehicles were detected 2.88 s earlier at a safety margin of about 6 m, while when the pitch was highly varied, vehicles were detected 5.05 s earlier at about 8 m).

3. Sound reception problems due to pedestrian characteristics (*e.g.*, age, hearing problems, etc.), for high background noise levels (*e.g.*, urban contexts), and for noise disturbances (use of headphones, cell phone, etc.) can negatively affect the efficacy of the AVAS sounds.

Poveda-Martinez *et al.* (2017) [54], by means of simulations done in a laboratory room where listeners wore headphones, studied the effectiveness and the noise impact of eight different AVAS sounds (selected among 64 sounds proposed by the industry) in relation to one HEV (Toyota Prius), driven at speeds above 20 km/h, and three urban environments (stopped vehicles at a traffic light, a pedestrian shopping area, and the vicinity of a playground). They compared AVAS sounds with the noises produced by HEV in electric (*i.e.*, without warning sounds) and ICE mode. They carried out a comprehensive statistical analysis based on different features (detection errors committed depending on the environment, listeners' reaction times, distance vehicle-pedestrian in different environments), and found that for having efficiency and limiting the noise impact of a warning sound, designers should focus on AVAS sound directivity, frequency of emission and intensity (which, for low speeds, should be greater than the noisiest background environment in which the vehicle works because of a small number of sharp peaks – harmonic components – located exclusively in the range 200–1000 Hz). Noises similar to those generated by ICEVs (*i.e.*, with high spectral density

bands combined with pronounced tonal components) increase the auditory detectability.

Figures 6 and 7 report the comparison between the AVAS sound prescribed by the ECE regulation [55, 56] (see solid black lines in Figures 6 and 7, which is called "Minimum AVAS sound" in the legend) and the AVAS sounds described by Sakamoto *el al.* (2012) [62] (see dashed lines in Figures 6 and 7). In more detail, Figure 6a shows the noise spectra of ICEVs moving at a constant speed of 10 km/h. In this case, the ICEVs noise is greater than the AVAS noise for frequencies greater than 1 kHz. Figure 6b shows the noise spectra of EVs moving at a constant speed of 10 km/h while the AVAS system is on and off. Note that the noise due to the combination of the EVs and the AVAS noises exceeds the minimum noise level required by the ECE regulation at about 600 Hz and 2000 Hz.

At the same time, Figure 7a shows that, even at 20 km/h, the SPL of ICEVs overcomes the minimum noise level required by the ECE regulation for frequencies greater than 1 kHz. Finally, Figure 7b shows how the AVAS noise allows EVs to respect the aforementioned level at 20 km/h.

Based on Figures 6 and 7, it is possible to conclude that properly designed AVAS sounds, complying with ECE regulation, are extremely important to ensure the proper level of safety for pedestrians.
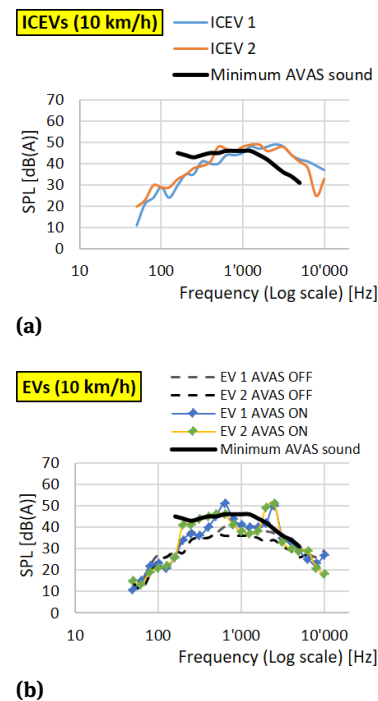

(a)

(b)

Figure 6: A-weighted Sound Pressure Level (ISO 362-1-1:2015) of AVAS sound *vs.* those of ICEVs and EVs (with AVAS on and off) moving at 10 km/h based on the study [62] and the ECE regulation [55].
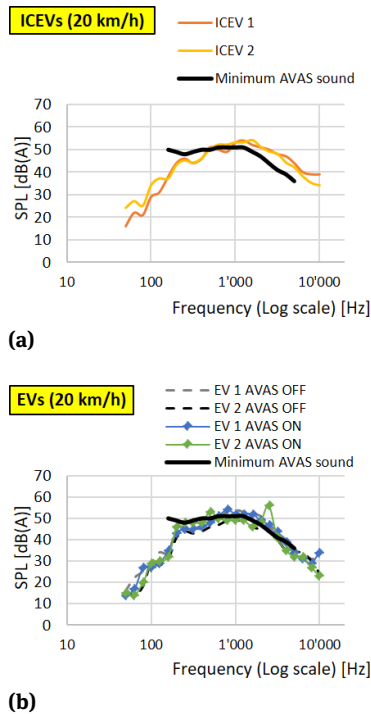
Figure 7: A-weighted Sound Pressure Level (ISO 362-1-1:2015) of the required AVAS sound *vs.* those of ICEVs and EVs (with AVAS on and off) moving at 20 km/h based on the study [62] and the ECE regulation [55].

2 Summary and conclusions

Table 1 and Figure 8 summarize results and perspectives in dealing with EVs versus ICEVs from a low-noise pavement perspective [8, 31, 32, 37, 45, 50, 52, 55, 56, 63–76].

Note that Table 1 reports a summary of the results discussed in Section 1.2 (Task 1 of this study). In more detail, based on more than one hundred measurements (considering vehicles fed with electric, gasoline and diesel and considering several vehicle models and sizes, including

motorcycles, trucks, and buses), the peaks of the Sound Pressure Level of both EVs (including pure electric and HEVs in electric mode) and ICEVs (light and heavy vehicles) were derived.

Figure 8 (out of scale) was created aiming at providing a tentative tool that can help the designers of the road pavements of the future. In particular, Figure 8 includes an overview of the main phenomena and road characteristics (including the frequency ranges where they occur/prevail over the others, respectively) that should be considered during the design process to obtain a low-noise pavement, *i.e.*:

- – Tires.
- – Pavement characteristics.
- – Type of mechanism this is more responsible for traffic noise generation.
- – Type of mechanism that is more responsible for the generation of the noise of EVs and ICEVs and the peaks of the related spectra.
- – AVAS sounds from EVs.

Each phenomenon and road characteristic plays an important role in the noise generation, and the EVs diffusion will alter the traffic noise spectra. Consequently, the low-noise road pavements of the future should be properly designed. On the one hand, some of the main characteristics reported in Figure 8 may be properly changed during the design process, while, on the other hand, the remaining characteristics may be neglected. This latter fact can allow paying more attention to the improvement of road performances, such as those related to durability, sustainability, safety and quietness.

Based on the analyses described above, the following main conclusions can be drawn:

1. The SPLmax difference between light EVs and ICEVs seems to change sign at about 90 km/h. Based on

Table 1: Summary of the results of Task 1.

Vehicle type	SPLmax [dB(A)] – Light vehicles							
	Speed (km/h)							
	R	0	10−20	30−40	50−60	70−80	90−100	110−120
EV	48.6	30.0	63.0	74.3	77.0	76.5	79.5	82.5
ICEVs	53.1	50.0	70.5	77.5	78.0	78.0	79.5	82.5
	SPLmax [dB(A)] - Heavy vehicles							
EV	n.a.	61.0	71.0	79.0	78.0	81.3	83.0	n.a.
ICEVs	n.a.	65.0	75.0	80.0	78.5	82.8	84.5	n.a.

Legend. EVs=Electric vehicles (*i.e.*, pure electric and HEV); ICEVs=Internal Combustion Engine Vehicles. R=Reverse; n.a.=not available. Note. Approximate data.
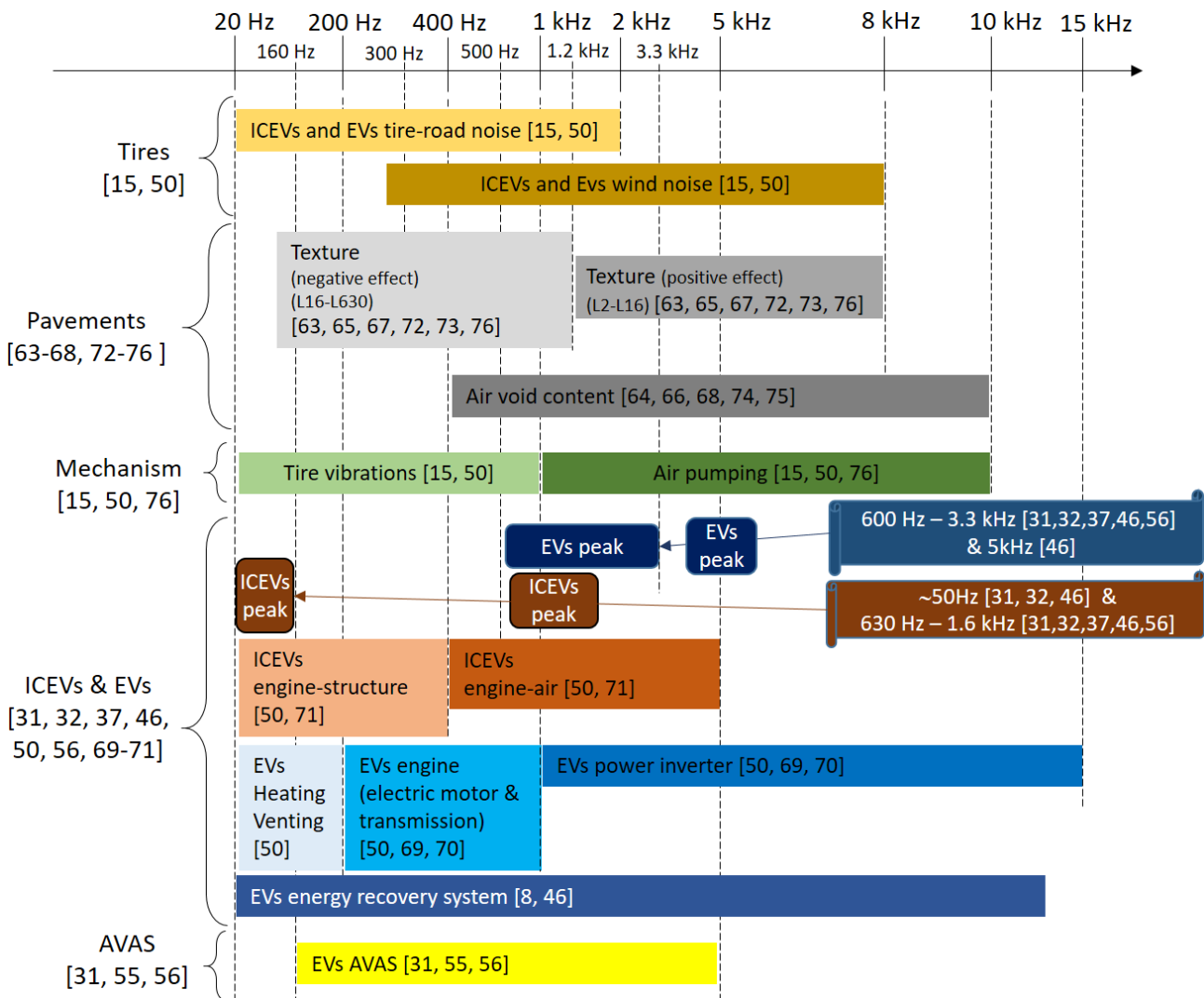
Figure 8: EVs *versus* ICEVs from a low-noise pavement perspective [8, 31, 32, 37, 45, 50, 52, 55, 56, 63–76].

these data, for lower speeds EVs have lower noise emissions, while for higher speeds ICEVs have higher noise emissions.

2. The SPLmax difference between electric heavy vehicles and ICE ones seems to follow the trend above, where speeds higher than 90 km/h are not relevant to the case.

3. ICEVs SPL spectrum has often two main maxima. The first is close to 30–100 Hz and is about 40–65 dB(A) (SPB, speed of 9–67 km/h). The second is close to 1 kHz and is about 60 dB(A)(SPB), speed of 9–67 km/h). More maxima at higher frequencies may be observed.

4. In contrast, for EVs, the maximum is located at about 0.5–2 kHz and is about 30–70 fB(A) for speeds in the range 9–67 km/h. This maximum usually appears sharper than the one of ICEVs. A supplementary maximum at about 5kHz has been observed.

5. AVAS SPL overrates EV and ICEV ones for low frequencies (< 1 kHz, v < 110 km/h).

In summarising:

– EVs result quieter than ICEVs at speeds lower than 90 km/h;

– At low frequencies, noise spectra related to ICEVs show a first peak that tends to disappear in the EVs-related spectra;

– The AVAS sound should be properly designed, *i.e.*, (1) It should avoid the excessive quietness of EVs. (2) Frequency modulations and pitch variation are needed to suggest to the pedestrian a vehicle speed variation (especially in urban contexts where low speeds are expected). (3) AVAS may allow EVs to generate secondary or new noises that must be properly studied.

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