

Influences of Electric Propulsion on Vehicle Vibro-acoustics

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The introduction of alternative power trains for low-carbon vehicles raise new sound quality issues which are sparsely documented in current literature. To this end, an electric conversion of a light commercial vehicle was investigated from a vibro-acoustic perspective. Power train sound and vibration was recorded for constant speed, wide-open-throttle and exterior drive-off tests. The test regime was repeated with a commercial combustion engine vehicle with a similar body and chassis. The resulting interior sound levels and spectrograms were compared to establish the key differences in the power train cues which are likely to influence the overall vehicle impressions of drivers. The electric vehicle is found to be noticeably quieter than its internal combustion engine counterpart. Furthermore, the characteristics produced by the engine firing orders in the lower and middle-frequency range contrast with the tonal stimuli in the middle- and high frequency range produced by the switching electronics and motor harmonics.

Additional keywords: Electric vehicles, spectrograms, interior sound

Nomenclature

Roman

f	frequency [Hz]
k	harmonic number
m_1	number of current phases
n	harmonic number
r_w	wheel rolling radius [m]
v	vehicle speed [km/h]
p	number of pole pairs
R_g	gear ratio
R_f	final drive ratio

Subscripts

f	fundamental stator supply frequency
r	radial electromagnetic force
n	harmonic number
m	mechanical motor speed
sw	switching

Acronyms

CAN	Controller Area Network
LCV	Light Commercial Vehicle
ICE	Internal Combustion Engine
WOT	Wide-open-throttle
PWM	Pulse-Width-Modulation

1 Introduction

The overall impression of a vehicle can be influenced by the sound sensation during wide-open-throttle acceleration (WOT). This sound can be used to convey experiences such as powerful and sporty or, as weak and boring [1].

Lennström *et al.* [1] found that the lower sound and vibration emissions from electric propulsion systems reduce the internal noise of electric vehicles. Additionally the authors noted that some participants in the psycho-acoustic evaluation of electric vehicles labeled the sound experience as “bland”. Interestingly, a study of consumer expectations regarding the owners of electric vehicles concurred with this impression [2] in that they were viewed in a negative light as people who “did not derive pleasure from driving” and “lacking that sense of fun”.

In a comprehensive review of seventy two luxury internal combustion vehicles, Jennings *et al.* [3] identify the key features that influence the perception of sound quality of vehicles. These are roughness or rumble, linearity, the dominance of the engine firing order, the sound pressure level of the low engine orders, the loudness level, the sharpness level, and the impulsiveness.

The aforementioned acoustic features resemble characteristics that have been defined from the study of predominantly internal combustion driven vehicles [3]. With alternative and electrically driven vehicles emerging on the market the question might be asked as to what the potential influences of electric drive trains are on the sound sensations of drivers.

Jennings *et al.* [3] state that novel power trains for low-carbon vehicles introduce new sound quality issues. These issues include reduced masking from the internal combustion engine (ICE) and new sound sources such as the motor and electronic switching devices. Additionally, the information conveyed to the driver by sound cues differs from that associated with a traditional sound experience and sometimes have non-automotive connotations [1]. In terms of exterior noise, the reduced audio-detectability of vehicles operating in electric-only mode raises safety issues particularly for blind pedestrians [4].

To date, public domain literature with regard to the vibro-acoustic attributes, sound quality and sound quality assessment of electric vehicles is sparse [1]. In the light of this, vibro-acoustic measurements were performed on an ICE light commercial vehicle (LCV) and an electric LCV conversion. The appropriate sound levels as well as sound- and vibration spectrograms are compared to highlight some key features that could influence the sound emitted by the respective drive trains. These features are likely to underpin the attributes that should be considered to accommodate customer perceptions of electric vehicles.

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2 Experimental Procedure

2.1 Vehicles under test

The power train sound and vibration of two half-ton LCVs were investigated. The electric vehicle entailed a custom conversion of a commercial LCV platform which was manufactured in 2003. The petrol powered ICE LCV was from the same manufacturer and model as that of the electric LCV with the exception that it was manufactured in 2008.

The vehicles were fitted with the same canopy and identical tires (refer Table 1). The tire rolling radius (for both vehicles) was determined to be 298 mm. The tire conditions were adjusted prior to testing to match the pressures reported in Table 1.

Table 1: The tire specifics and load distribution of the electric and ICE LCVs.

	Electric	ICE
Tire pressure		
Front	3 bar	3 bar
Rear	2.2 bar	2.2 bar
Tire type		
Front	185/70R14 88T Dunlop	185/70R14 88T Dunlop
Rear	185/65R15 Green Michelin	185/65R15 Green Michelin
Load distribution		
Total mass [kg]	1390	1420
Front axle mass [kg]	570	600
Rear axle mass [kg]	820	820

A custom built frame was used to mount two battery trays in the load-bay of the electric LCV. The ICE LCV was ballasted with sand bags in order to simulate the load and load distribution of the batteries which is carried by the electric vehicle. Although the ICE vehicle was 30 kg heavier than its electric counterpart, both vehicles were loaded to a rear axle mass of 820 kg.

The drivetrain of the ICE LCV comprised a 1.3 litre, in-line four cylinder engine with a power output of 55 kW at 5500 rpm. The relevant transmission ratios for the five-speed manual gearbox are presented in Table 2.

Table 2: Gearbox and transmission ratios of the ICE LCV.

Gear	Gear ratio	Test
1 st Gear	3.58	Drive-off
2 nd Gear	1.93	20 km/h, WOT
3 rd Gear	1.41	30 km/h, 40 km/h, 50 km/h
4 th Gear	1.11	60 km/h, 70 km/h, Drive-by
5 th Gear	0.88	80 km/h, 90 km/h, 100 km/h
Final Drive Ratio	4.25	

The electric power train was assembled from off-the-shelf components including a permanent magnet motor and a single transmission gearbox for which the specifics are provided in Table 3.

Table 3: Specifics of the electric drive train installed in the LCV.

Peak Torque	300 Nm
Peak Power	125 kW
Continuous Power	45 kW
Torque limit	200 Nm
Max speed	8000 rpm
Full power	at 250-425 VDC input
Transmission ratio	6.54:1
Motor :Number of stator slots	108
Motor: Number of pole pairs (p)	9

2.2 Test protocol

On the day of testing the weather conditions were fair with an intermittent breeze. In the absence of interior acoustic testing facilities the experiments were performed outdoors. The two right hand drive vehicles were tested back-to-back on the same day.

The measurements were performed on a flat racetrack with a smooth tar surface in urban surroundings. Data was acquired at a sample rate of 44 kHz using a highly-portable, four-channel Squadriga measurement system from HEAD Acoustics GmbH [5].

Sound pressure was recorded at the right- and left ear positions with a binaural headset which was worn by the front passenger. Acceleration measurements were made on the engine/motor casing with two PCB Piezotronics accelerometers which were magnetically mounted in the fore-aft (X) and lateral (Y) vehicle axes (see Figure 1).

A Baumer electric speed sensor was mounted to the left rear brake calliper bracket of the vehicle. Sponge tape was stuck to the inner surface of the rim to interrupt the light pulse once per revolution as shown in Figure 2. The rotational frequency of the wheel was determined from the pulse signal by using a tachometer code in LMS Test.Lab software.

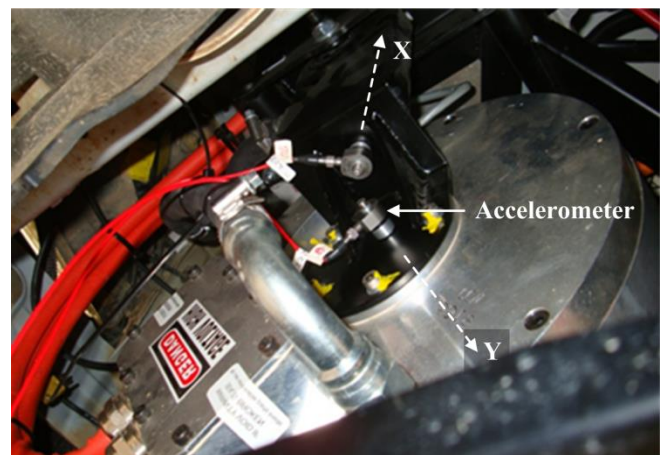


Figure 1: The mounting of two PCB Piezotronics accelerometers on the motor casing of the electric motor.

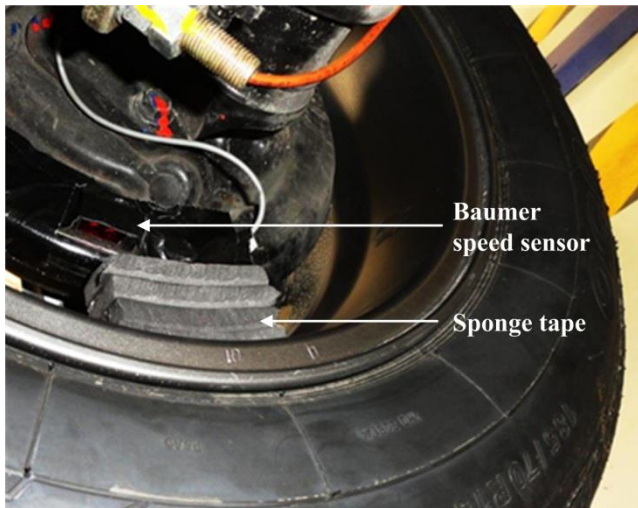


Figure 2: A photograph showing the sensor mounting for recording the wheel rotation frequency.

The vehicle speed was calculated from the wheel frequency by multiplying the frequency of the pulse signal (wheel revolutions per second) with the rolling circumference of the wheel and converting the time units:

$$v = 3.6 \times 2\pi r_w f_w \quad (1)$$

The mechanical speed of the motor / engine is determined from the rotational frequency of the wheel by multiplying with the drive-to-wheel ratio:

$$f_m = R_g R_f f_w \quad (2)$$

Two persons participated in the measurements: the driver who controlled the vehicle according to the desired test protocol and a test operator in the passenger seat who prompted the measurements and wore the binaural headset. All measurements were performed with the windows shut and the ventilation off. Neither of the vehicles offered the option of air-conditioning.

Interior sound and vibration was recorded during constant speed and wide-open-throttle (WOT) acceleration tests. Constant speed investigations were performed in 10 km/h increments between 10 km/h and 100 km/h. The test at 10 km/h in the ICE vehicle was not possible as the vehicle speed exceeded 10 km/h when minimum throttle was applied. The gear selections for the constant speed drives in this vehicle are reported in Table 2.

For the WOT experiments the driver applied full throttle to the stationary vehicle and commenced with a “free” coast-down at a speed of approximately 100 km/h. Regenerative braking was enabled for the tests on the electrically driven vehicle. The ICE vehicle was driven in second gear.

Exterior sound measurements were performed for two pedestrian scenarios. Sound pressure was recorded with a binaural head set by a stationary observer who was facing the road as if crossing the street from the passenger side.

Drive-off measurements entailed accelerating the vehicle by applying part-throttle (slow but steady acceleration) from a parked position next to the observer.

Drive-by tests were conducted by driving past the stationary observer at a constant speed of 40 km/h. The observer initiated the measurement when the vehicle passed a marker on the road. The driver sounded the horn of the

vehicle once when the vehicle passed a second marker. This allowed some reference by which the data could be synchronized.

3 Results

3.1 Constant speed drives

The interior noise of the ICE and electric LCVs are compared in terms of the A-weighted sound pressure levels as presented in Figure 3.

At low speed the interior sound level of the electric vehicle approaches that of the environmental noise. The interior sound level of the electric LCV is quieter than the ICE LCV up to a vehicle speed of about 80 km/h. Beyond 80 km/h the sound levels converge as rolling- and aerodynamic noise factors become dominant in determining the interior sound level.

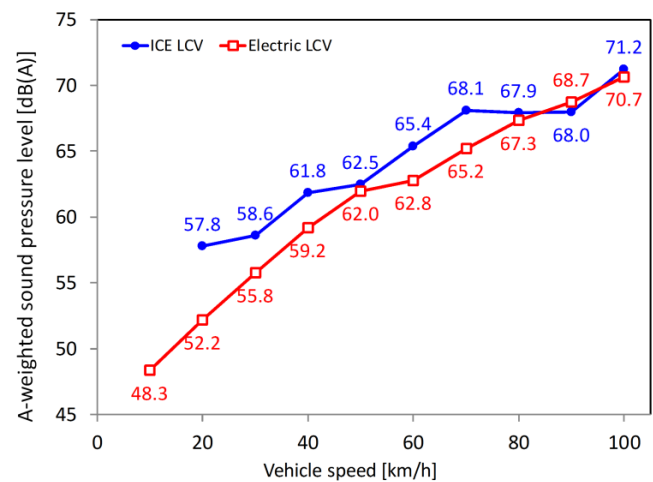


Figure 3: A-weighted sound pressure levels for constant speed drives.

3.2 WOT acceleration

3.2.1 Time domain sound pressure levels

A-weighted, time domain, sound pressure levels were determined with the Psychoacoustic Metrics add-in in LMS Test.Lab Signature Processing software. This commercial tool calculates a dynamic sound pressure level according to the IEC 651 and ANSI SI.4-1983 standards. A time constant of 0.125 s was selected as is standard practice for the analysis of automotive signature sound levels.

The time domain, sound pressure levels are compared for the ICE and electric LCVs in Figure 4. Two WOT experiments are presented for each vehicle to indicate the lower and upper ranges of variability encountered. It is clear that the interior of the electric vehicle is quieter than the ICE vehicle despite the potentially superior acoustic package of the 2008 vehicle platform. This result is especially conservative when considering the lack of refinement in the prototype electric drive assembly. Notice that the sound pressures of the vehicles do not reach convergence below 100 km/h.

The growth in the interior sound levels for the electric vehicle is more linear than that of the ICE vehicle which is characterized by sound levels that vary dramatically on several occasions. There is a sharp initial increase in the

sound pressure at low speed with rapid rises over and above the increasing trend at 25 km/h, 50 km/h and 70 km/h.

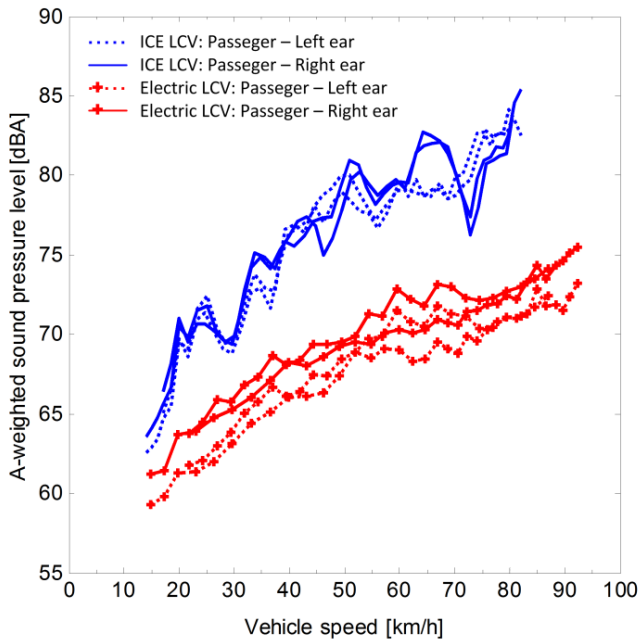


Figure 4: A comparison of the (A-weighted, time domain, sound pressure level time constant = 0.125 s) for WOT acceleration.

Further consideration of Figure 4 shows that the sound pressure at the right ear (interior-side ear) of the passenger is dominant at lower vehicle speeds. This is explained by the relative contributions of the drive train-, rolling- and airborne sound as the vehicle accelerates. At lower speed the inside ear is better positioned to experience the noise emitted from the drive train. At higher speeds the outer (left) ear is expected to experience a more rapid rise in interior sound pressure as airborne noise grows around the outer vehicle surfaces.

3.2.2 Spectrograms

Spectrograms were generated by combining the linear, peak, autopower spectra of the vibration and acoustic (A-weighted) time signals measured during WOT experiments. Each spectrum comprised of 4096 spectral lines which resulted in a frequency resolution of 5.4 Hz and a frame size of 0.2 seconds. This analysis provides an indication of the frequency range of the drive train excitation as well as the audible sound cues inside the passenger cabin.

The vibro-acoustic waterfalls of the two vehicles differ remarkably with respect to the following attributes:

- 1.) The electric vehicle sound signature does not display any dominant motor orders in the low frequency range (Figure 5(a)). By comparison, the second engine order along with some less dominant harmonics, are apparent below 200 Hz for the ICE LCV as shown in Figure 6(a). This is explained by the engine firing sequence for a four cylinder engine according to which the ignition system must fire once for every 180 degrees of crank rotation. This results in two ignitions per revolution of the engine and thus the second engine order.
- 2.) The sound and vibration spectrograms of the ICE LCV are characterized by random (or broadband) sound and

vibration as a result of engine combustion. In contrast, the electric motor harmonics have a tonal nature and occur in the mid- and high frequency ranges (Figure 5 (b) and (c)). The most audible order is the 54th motor order (6th harmonic of the current fundamental frequency) that runs from 0 to 5 kHz. This tonal order does not receive appreciable masking from broadband excitation sources as can be seen from the significantly lower sound levels on the spectrogram.

The many sources of dominant harmonics in electric motor sound signatures are summarized by Gieras *et al.* [6]. These sources were studied to determine possible explanations for the tonal harmonics in the electric drive train signature. It was found that a major cause of sound and vibration in the present motor is attributed to inverter harmonics. These harmonics cause radial magnetic forces which are ascribed to the product of the stator harmonics of the same number.

The frequencies of the radial forces caused by the product of the stator harmonics of the same number are given by:

$$f_{r,n} = 2nf_f \quad (3)$$

Where,

$$f_f = pf_m = 9f_m \quad (4)$$

and

$$n = 2km_1 \pm 1 \text{ and } k = 0,1,2,3, \dots \quad (5)$$

The permanent magnet motor was driven by a three-phase current, therefore $m_1 = 3$.

3.) The vibration spectrogram from the electric motor in Figure 5(c) displays a fan-like order pattern around 12.5 kHz.

This is explained by the interaction between the switching frequency and the inverter harmonics for a pulse-width -modulation (PWM) control strategy [7]. Radial magnetic forces are produced by inverter harmonics through the interaction of the switching frequency and higher time harmonics [6]. The most dominant of these forces is the interaction between the fundamental field harmonic and higher time harmonics for which the frequencies are:

$$f_{r,n} = |\pm f_n - f_f| \quad (6)$$

Where f_n is given by:

$$f_n = n'f_{sw} \pm n''f_f \quad (7)$$

Note that if n' is an odd integer then n'' is an even integer and vice-versa.

This phenomenon is not noticeably audible (Figure 5(b)) as it centers around a high frequency where the human ear is less sensitive to sound.

4.) Figure 5(c) indicates that the fan-like switching pattern stops after the first 10 seconds of acceleration and resumes again in the course of the run-down. The vehicle CAN (Controller Area Network) logs confirmed that the electric motor control strategy is altered to trapezoidal mode control at this point. This transition in control strategy results in a non-sinusoidal drive current [7] which is linked to a prominent change in vibration signature (at about 10 and 25 seconds in Figure 5(c)). Acoustically this transition is also associated with the onset of an audible electric motor

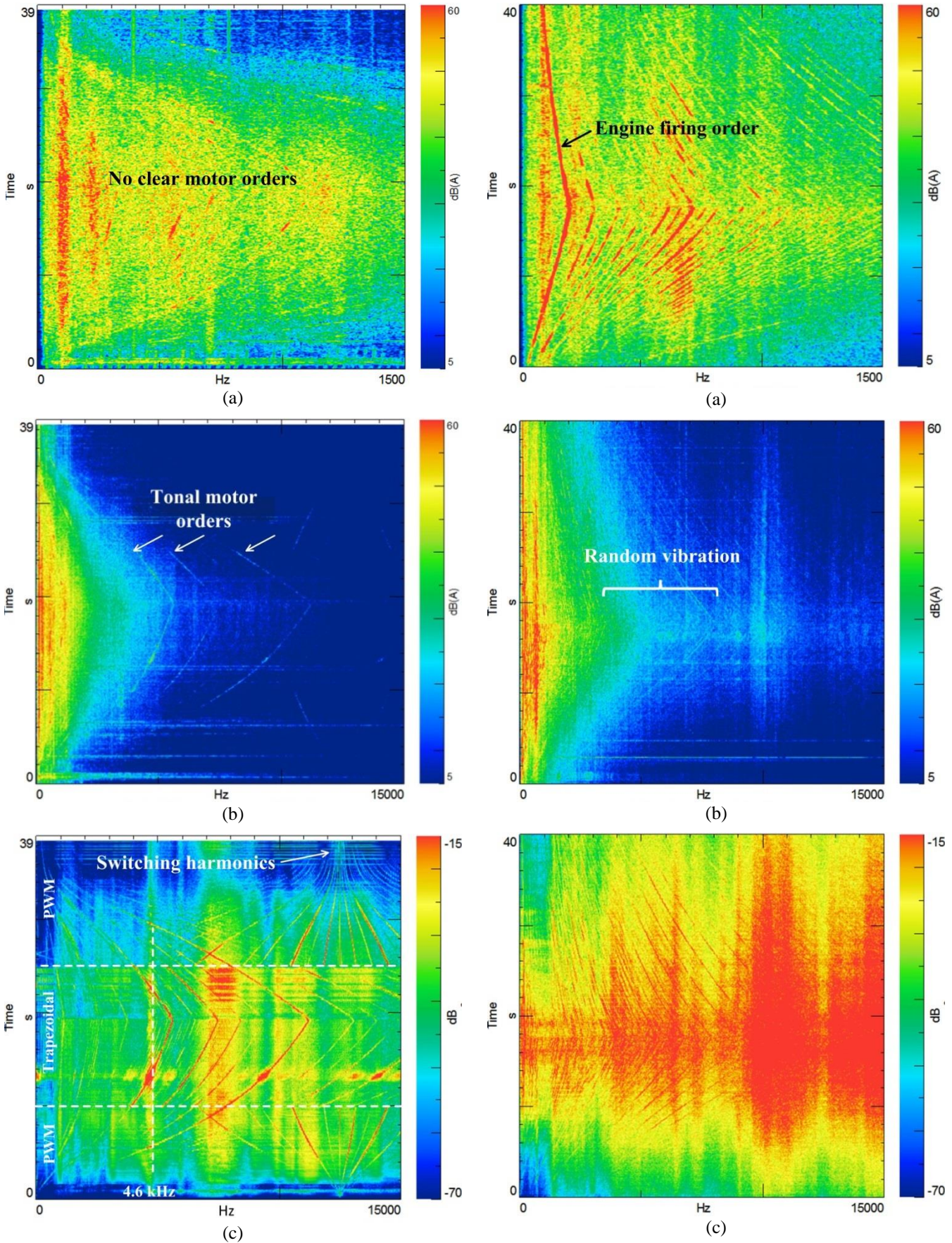


Figure 5: Spectrograms of the A-weighted sound pressure (a) below 1 kHz and (b) 15 kHz and the (c) vibration below 15 kHz for the electric LCV WOT.

Figure 6: Spectrograms of the A-weighted sound pressure (a) below 1 kHz and (b) 15 kHz and the (c) vibration below 15 kHz for the ICE LCV WOT.

whine. Investigation of the acoustic and vibration spectrograms indicates that this whine arises from frequencies linked to the 54th, 72nd, 90th and 108th motor orders (the 3rd, 4th, 5th and 6th harmonics of the current fundamental frequency).

5.) Shortly after the switch to trapezoidal mode control the dominant order 54 (or the third harmonic of the fundamental current) passes through a resonance frequency (at 4.6 kHz) of the stator housing which gives rise to a sharp increase in the sound level at that frequency. The combination of a prominent order and a resonance in this frequency range results in an increase in the whining noise to ear-piercing proportions.

3.3 Exterior noise

A quiet section of track was selected for the exterior noise investigation. As the measurements were performed outdoors some interference was encountered from occasional bird twitter and moderate gusts of wind. The ambient sound pressure level, as measured by the observer, varied between 47 to 48 dB(A) for the exterior sound measurements of both vehicles.

Typical results from the drive-off tests are compared in Figure 7, which shows the time-domain sound pressure level for the ICE- and electric LCV. Aside from the gear chatter when the electric motor engages through the gearbox, the sound emissions of the electric LCV approach that of the ambient noise at low speed. To an outside observer the sound emitted by the acceleration of the ICE vehicle would be noticeably louder especially during initial acceleration.

The peak time-domain sound pressure levels are reported in Figure 8. It is shown that the peak sound pressure level during the electric vehicle drive-off test is roughly 8 dB(A) less than that of the ICE vehicle. Subjectively an observer is likely to experience the drive-off sounds of the electric vehicle as ‘obviously’ more quiet or even ‘double’ as quiet.

The results presented in Figure 8 and Figure 9 show that the drive-by sound levels (at 40 km/h) of the two LCVs are more similar and that the risk of not hearing an approaching vehicle should be comparable. This indicates that the pass-by test at 40 km/h likely exceeds the cross-over speed which is defined as the vehicle speed where tire noise, wind resistance and other factors allow the audio detection of an approaching vehicle [4].

Further observations from Figure 9 show that the sound pressure peaks first in the ear on the side from which the vehicle is approaching and that this peak is slightly higher. The difference between the masking sound of the environment and the peak noise when the vehicle passes by is roughly 20 dB(A) which would be perceived by the observer as a quadrupling in loudness.

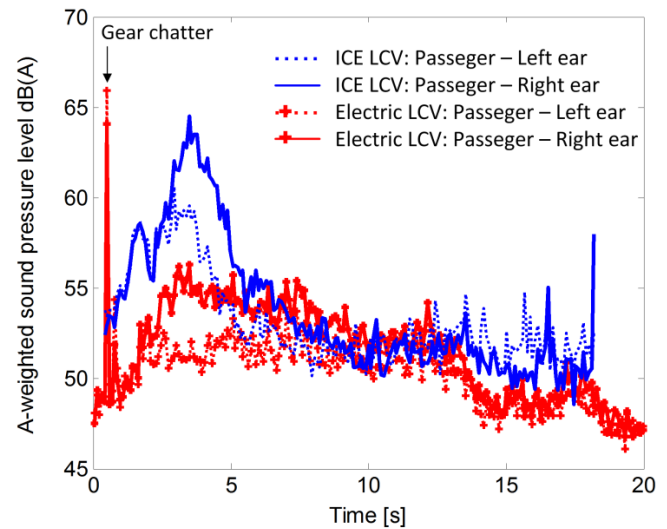


Figure 7: The A-weighted time-domain sound pressure level for an exterior drive-off experiment.

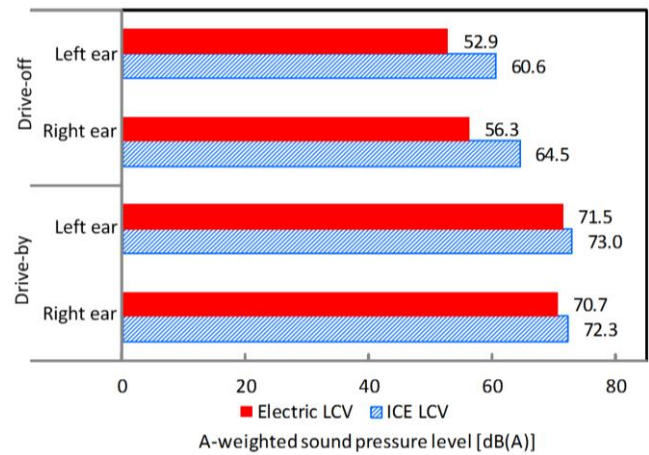


Figure 8: A diagram showing a comparison of the peak A-weighted time-domain sound pressure levels for exterior noise measurements.

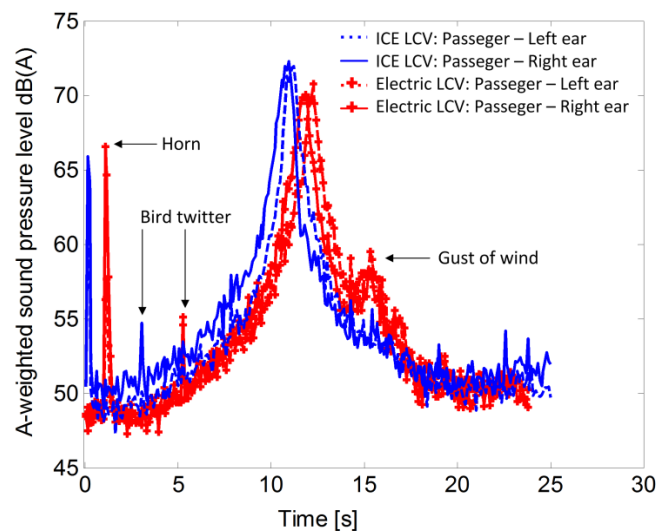


Figure 9: The A-weighted time-domain sound pressure level for an exterior drive-by experiment.

4 Discussion

The present investigation points to a clear distinction between electric and ICE vehicle sound signatures. The most prominent differences include more audible drive train cues from the ICE engine as well as a dominant firing order below in the low- and mid-frequency ranges.

In contrast the electric drive produces tonal orders above 1 kHz which could lead to whining sounds if not isolated sufficiently. The above conclusions concur with the findings of Lennström *et al.* [1] in their investigation of an electric Volvo C30.

Results show that the A-weighted sound pressure levels of the interior noise appear to converge beyond 80 km/h. Garay-Vega *et al.* [8] have shown that the exterior sound of electric and combustion vehicles converges at the cross-over speed, for vehicles on a similar platform. The present investigation shows that this observation could possibly extend to the interior sound for constant speed drives.

The interior sound level during WOT experiments resulted in significantly higher sound levels when compared with the constant speed runs. This is attributed to the increase in power train sound and vibration. In contrast with the constant speed tests, the WOT sound levels of the two vehicles did not converge below 100 km/h. A similar result is presented by Mell and Meier who performed an investigation of electric- and diesel Mercedes Benz A-Class vehicles [9]. The existing associations of drivers with the major increase in noise and vibration during WOT acceleration in ICE vehicles potentially highlights another factor which could contribute to a “dull” driving experience in electric vehicles.

The growth in the interior sound levels (during WOT) for the electric vehicle is more linear than that of the ICE vehicle. The sound signature of the ICE is characterized by sound levels that vary dramatically on several occasions. There is a sharp initial increase in the sound pressure at low speed with rapid rises over and above the increasing trend at 25 km/h, 50 km/h and 70 km/h.

Although its strong linearity is considered to be a positive attribute, it is unlikely that the sound signature of the electric vehicle would be associated with a powerful sensation. The reason is that the sound power increases gradually in the early stages of vehicle acceleration with no strong orders on the low-frequency range, whereas initial steep changes in the low frequency content from stand-still enhances the powerful dimension [3].

In the present investigation the dominant orders of the motor are spaced far apart and do therefore not modulate with each other to cause a sensation of roughness in the sound. Although a smooth sound is a positive sound attribute, roughness is associated with sensations linked to a powerful vehicle acceleration experience [3].

The switching strategy of the inverter clearly affected the signature sound of the electric vehicle under investigation. It seems that the sinusoidal current produced by a PWM strategy suppressed higher order harmonics. A switch in motor control strategy to trapezoidal control adversely affects the signature sound of the electric vehicle in that it resulted in severe motor whine and prominent higher harmonics.

The convolution of the rotor and stator harmonics with the switching electronics causes a symmetrical order pattern around the switching frequency. If this phenomenon occurs in the audible range this could lead to tonal sounds that descend in pitch as the vehicle accelerates. The interference of electric motor harmonics and the switching phenomena should also be considered as this could lead to tonal bursts that disturb the homogeneity of the signature sound. Ideally the switching phenomena should be kept outside the audible range.

Mechanical resonances in the motor structure can lead to a sharp increase in sound pressure level in the passenger cabin. Although this is also the case with ICE engines the difference in the frequency ranges of excitation implies that electrical motor structures should be resistant to higher order vibration modes.

In terms of exterior sound, the lack of idle noise leads to sound emissions that do not exceed ambient noise during the early stages of the drive-off experiment. This situation is deficient in the communication of sound cues to pedestrians in the vehicle environment. This supports existing observations that refer to the potential threat that electric vehicles pose to pedestrians because they are particularly hard to hear at low vehicle speeds [10]. Garay-Vega *et al.* [11] found that ambient sound levels influence the response time of blind pedestrians who were tasked to detect hybrid electric vehicles that pass by in electric mode. Sound mitigating systems are being suggested as a means by which quiet vehicles can warn pedestrians about their proximity. Currently the thinking is that such a sound generator should adjust its level of sound output according to sound levels in the environment. Thus, the potential exists to combine the advantages of quieter city environments and pedestrian safety [8].

Drive-by experiments at 40 km/h result in similar noise levels for the ICE and electric LCVs. This speed likely exceeds the cross-over speed where wind and tire noise provide pedestrians with the information needed to reasonably detect a nearby vehicle.

5 Conclusions

The electric LCV was found to be more quiet than the ICE LCV during WOT acceleration, constant speed drives and drive-off tests. For constant speed drives the sound pressure levels of the LCVs converge whereas this is not the case for WOT acceleration. Furthermore, random noise and low-frequency firing orders are contrasted against tonal motor harmonics in the mid- and high frequency ranges. Further considerations include the selection of the switching frequency and control strategy for the electric motor. The quiet exterior sound of electric vehicles below the cross-over speed is likely to have implications for audio-detectability and pedestrian safety. Possible factors that contribute to a “dull” electric vehicle driving experience could be the lack of low frequency engine orders and roughness, as well as the lower noise and vibration outputs from the electric motor when accelerating at WOT.

Future work includes the analysis of commercial electric vehicle drive-train sound stimuli and the development of a subjective assessment framework to determine customer satisfaction. Additionally, the acoustic enhancement of the

interior and exterior sound could be considered to improve pedestrian safety and increase driver satisfaction. The question remains if electric vehicles should be designed to sound like ICE vehicles or if a unique acoustic signature could be created to instill the thrill of driving whilst achieving a quieter interior and exterior vehicle environment.

6 Acknowledgements

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