DOI: 10.61782/fa.2025.0227

FORUM ACUSTICUM EURONOISE 2025

COMPARING MEASURED PASS-BY LEVELS OF ACCELERATING BATTERY ELECTRIC CARS AND COMBUSTION ENGINE CARS

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ABSTRACT

Road traffic is the noise source affecting most people, especially near major routes in densely populated areas. Battery Electric Vehicles (BEV) are presumed quieter than Internal Combustion Engine Vehicles (ICEV), but under which conditions and by how much is uncertain. To quantify the pass-by level differences between both propulsion concepts, measurements were conducted with nine pairs of comparable BEVs and ICEVs, where controlled runs with target speeds and accelerations were performed on a closed test track. Kinematics were measured by RTK-GNSS and sound exposure levels were evaluated with microphones beside the track. This paper presents first results from these measurements. From the collected data, pass-by level models as functions of speed and acceleration were developed for each vehicle. In an attempt to assess the acoustical effects of urban driving behavior, these models were linked to a frequency distribution of speed and acceleration acquired from driving data recorded in real traffic. On average, no level difference between the propulsion concepts was found at constant speeds above 30 km/h. At low speed and high acceleration, BEVs exhibit 5 dB lower levels. This difference diminishes with increasing speed and decreasing acceleration, becoming negligible above 40 km/h.

Keywords: BEV, ICEV, pass-by level, acceleration, urban road traffic

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1. INTRODUCTION

As stated in the latest EEA report on Europe's air pollution [1], road traffic remains the primary noise source affecting the most people, with high prevalence in urban areas. Pass-by noise from passenger cars is commonly regarded as the sum of two major contributions: propulsion noise and tire noise [2, 3]. For passenger cars driving at constant speed, the cross-over speed above which the A-weighted tire noise level surpasses that of the propulsion can typically be found within the range 20–30 km/h [3]. It is expected that under acceleration, the combustion engine's noise and consequently the described cross-over speed increase. Previous works [4, 5] have shown that accelerating battery electric vehicles (BEV) produce smaller $L_{\mathrm{AF,max}}$ and $L_{\mathrm{A,eq}}$ than internal combustion engine vehicles (ICEV). In this study, the A-weighted sound exposure levels L_{AE} of BEVs and ICEVs are compared under real urban driving conditions. The required data was gathered in a measurement campaign of nine BEVs and nine ICEVs. The ICEVs were selected based on a matching algorithm to form comparable pairs with the BEVs. In the campaign, all vehicles completed run sequences with target speeds and accelerations on a closed track, equipped with sensors to monitor and record vehicle kinematics while passing by multiple microphones along the track. With the acoustic and kinematic data obtained, vehicle-specific pass-by level models were established that allow comparison between the individual cars within each pair and of the two propulsion systems by pooling the nine vehicles per system.

Sec. 2 introduces the methodology. Sec. 3 outlines the measurement campaign. First results of this study are presented in Sec. 4.

2. METHODOLOGY

2.1 Selection of Similar ICEVs

Nine different BEVs covering seven car body styles were selected for the measurements. A similar ICEV to each BEV was identified to form pairs allowing the comparison of the propulsion concepts. To find similar cars, a matching algorithm was developed that evaluates five key criteria that strongly influence the customer's purchase decision, namely the dimensions height, length, and width, the long-term mass-to-power ratio, and the manufacturer's suggested retail price in Switzerland. The match indicator M is calculated by Eqn. (1). The absolute deviation in the criterion X between the BEV j and all ICEVs i with the same body style C (class) are determined. This deviation is statistically normalized by dividing by the standard deviation in this criterion of all cars within the same class. The weighted sum of all normalized deviations produces M. In this study, all criteria were equally weighted ($w_X = 20\,\%$).

$$M(i,j) = \sum_X w_X \cdot \frac{\left|X_{i,C(j)} - X_j\right|}{\sigma_{X,C(j)}} \qquad (1)$$

A smaller number M indicates a better match, therefore sorting in ascending order results in a ranking. If a corporate group's portfolio offered BEV and ICEV models based on the same platform, they would be considered to match best, regardless of M. The highest-ranking ICEVs available were obtained for the measurement campaign. Only cars that, at the time, could be purchased new from the manufacturer were selected. Manual transmission models were excluded (a) to avoid the influence from the driver's individual shifting behavior and (b) because since 2018 the majority of the current Swiss vehicle fleet is equipped with automatic transmissions [6]. The similarities of the selected vehicles within the pairs were compared in terms of the five matching criteria and further parameters such as tire width.

2.2 Driving Profiles

Driving profiles with different target speeds and accelerations were defined. To sufficiently represent urban traffic, these profiles covered speeds up to 60 km/h. The profiles analyzed in this paper are defined by the following target (index 't') kinematics. Constant speed ($a_t = 0\,\mathrm{m/s^2}$): $v_t = 30\,\mathrm{km/h}$, $v_t = 50\,\mathrm{km/h}$, and $v_t = 60\,\mathrm{km/h}$ and constant acceleration from a standstill: $a_t = 0.8\,\mathrm{m/s^2}$, $a_t = 1.6\,\mathrm{m/s^2}$, and $a_t = 2.4\,\mathrm{m/s^2}$.

3. MEASUREMENT CAMPAIGN

3.1 Measured Vehicles

Tab. 1 lists all measured pairs of cars, their classes (i.e. body styles) and the closest matching rental car (ACCS) code [7]. Prior to the measurement campaign, all cars were professionally checked for their road-worthiness and equipped with new OEM tires that were run in for 500–1000 km. Drive modes were always set to standard ('Comfort', 'Normal', etc.), but engine start-stop systems were switched off.

Before their respective series of measurement runs, the cars were driven in usual manner on public roads for at least 30 min to warm up the tires and fluids. Tire pressures were adjusted to manufacturer specification and fluid and tire temperatures were measured before and after each run series. All measurement runs were performed by two professional drivers.

3.2 Setup and Conditions

Measurements were taken on two consecutive days in May 2024 at 8–22 °C and wind speeds below 3 m/s. The TCS test track south of Thun, Switzerland, shown in Fig. 1, offers a 105 m long lane which was defined as the measurement section. It is paved with a dense asphalt concrete AC 11 S. Texture measurements performed with a profilometer (M+P FLaSH|M) showed no anomalies.

The cars were equipped with custom electronics combining consumer-grade inertial measurement units (IMU, InvenSense ICM-20948), multi-constellation GNSS receivers (u-blox ZED-F9P) & antennas (Taoglas MagmaX2), and micro controllers (PJRC Teensy 4.1) to control the sensors, read, and log their outputs. Mapped to a windshield-mounted LED strip, the live IMU read-out provided visual feedback to aid the drivers keeping the acceleration within tolerance to the current target value.

Figure 1. Photo of the test track and measurement setup. Seven microphones (right) are capturing exterior noise from the VW Multivan T7 passing by.

Table 1. BEV/ICEV pairs for the measurement campaign. Third letters "A" in the ACCS Codes denote automatic transmission, followed by "E" for electric engines and "V" for petrol engines or "D" for diesel engines in the ICEVs.

Pair ID	BEV	ICEV	Class	ACCS Code
1	Peugeot e-208	Peugeot 208	Compact	EDA E/V
2	VW ID.3	Seat Leon	Lower-Range Mid-sized	CDA E/V
3	Volvo EX40	Volvo XC40	Mid-sized SUV	IFA E/V
4	Tesla Model Y	Skoda Kodiaq	Large SUV	SFA E/D
5	Skoda Enyaq	Seat Tarraco	Large SUV	SFA E/D
6	Tesla Model 3 Perf.	Mazda 6	Mid-Range Mid-sized	SDA E/V
7	Volvo EX30	Mazda CX-3	Small SUV	CFA E/V
8	Hyundai Ioniq5	Ford Kuga	Large SUV	IFA E/V
9	VW ID.Buzz	VW Multivan T7	Large Van	FVA E/D

A static base station with identical hardware was positioned close to the track. With this setup, high-precision kinematic data was obtained by post-processing the base and rover GNSS data (RTK technique [8]). All GNSS data were recorded at a sampling rate of 15 Hz. A state-of-the-art GNSS device (Racelogic VBOX) allowed monitoring the driving speed independently from dashboard tachometers.

Seven class 1-compliant microphones (NTi M2230) were set up in standard position [9], i.e. lateral 7.5 m from the lane center and 1.2 m above ground, as can be seen in Fig. 1. Microphone signals were recorded with a multichannel audio recorder (SoundDevices MixPre-10), calibrated with a class 1 microphone calibrator (Brüel & Kjær 4231) and synchronized via NTP [10] to ensure audio and kinematic synchrony.

3.3 Quality Criteria

During each measurement run, kinematics were monitored. A run was declared invalid, if the tolerance band of $a_\mathrm{t} \pm 0.25\,\mathrm{m/s^2}$ was left for more than 2 s (accumulative) or, during constant speed runs ($a_\mathrm{t} = 0\,\mathrm{m/s^2}$), if the speed was outside the $v_\mathrm{t} \pm 2\,\mathrm{km/h}$ tolerance band at any time. Invalid runs were repeated until at least three valid, independent measurements were taken.

In the post-processing, all pass-bys with $SNR < 10\,\mathrm{dB}$ were excluded from further analysis.

4. RESULTS

4.1 Measured Pass-by Levels

Analysis of the combined acoustic and kinematic data of all pass-bys formed 1208 value triplets $[L_\mathrm{AE}, v_\mathrm{PB}, a_\mathrm{PB}]$ that meet the quality criteria described in Sec. 3.3. L_AE is the A-weighted sound exposure level of a pass-by with the measured (not target) speed v_PB and acceleration a_PB at the instance of pass-by. Fig. 2 shows the pass-by levels of the individual cars measured at target speeds of 30 km/h (top) and 50 km/h (bottom) without acceleration (left) and with a target acceleration rate of $1.6\,\mathrm{m/s^2}$ (right). The horizontal lines represent the mean energy (ME) of the pass-by levels in the same profile over all cars with the same engine type. The average standard deviation $\overline{\sigma} = 0.4\,\mathrm{dB}$ over all levels of individual pass-bys with common kinematics shows that the results are robust and reliable. For constant speed profiles, the pass-by levels cover the ranges 61–67 dB at 30 km/h, 68–72 dB at 50 km/h (see Fig. 2), and 70–74 dB at 60 km/h. The differences between all $\mathrm{ME_{BEV}}$ and $\mathrm{ME_{ICEV}}$ are smaller than 0.5 dB which is below the measurement uncertainty.

Under acceleration, pass-by level differences between BEVs and ICEVs are more pronounced. These differences are maximal at high acceleration rates and low driving speed. At an acceleration of $1.6\,\mathrm{m/s^2}$, the ME differences between BEVs and ICEVs amount to $-2.8\,\mathrm{dB}$ at $v_\mathrm{PB} = 30\,\mathrm{km/h}$ and $-1.1\,\mathrm{dB}$ at $v_\mathrm{PB} = 50\,\mathrm{km/h}$. A conceivable explanation is an increased propulsion noise of the combustion engines with fading dominance over rolling noise at higher speed.

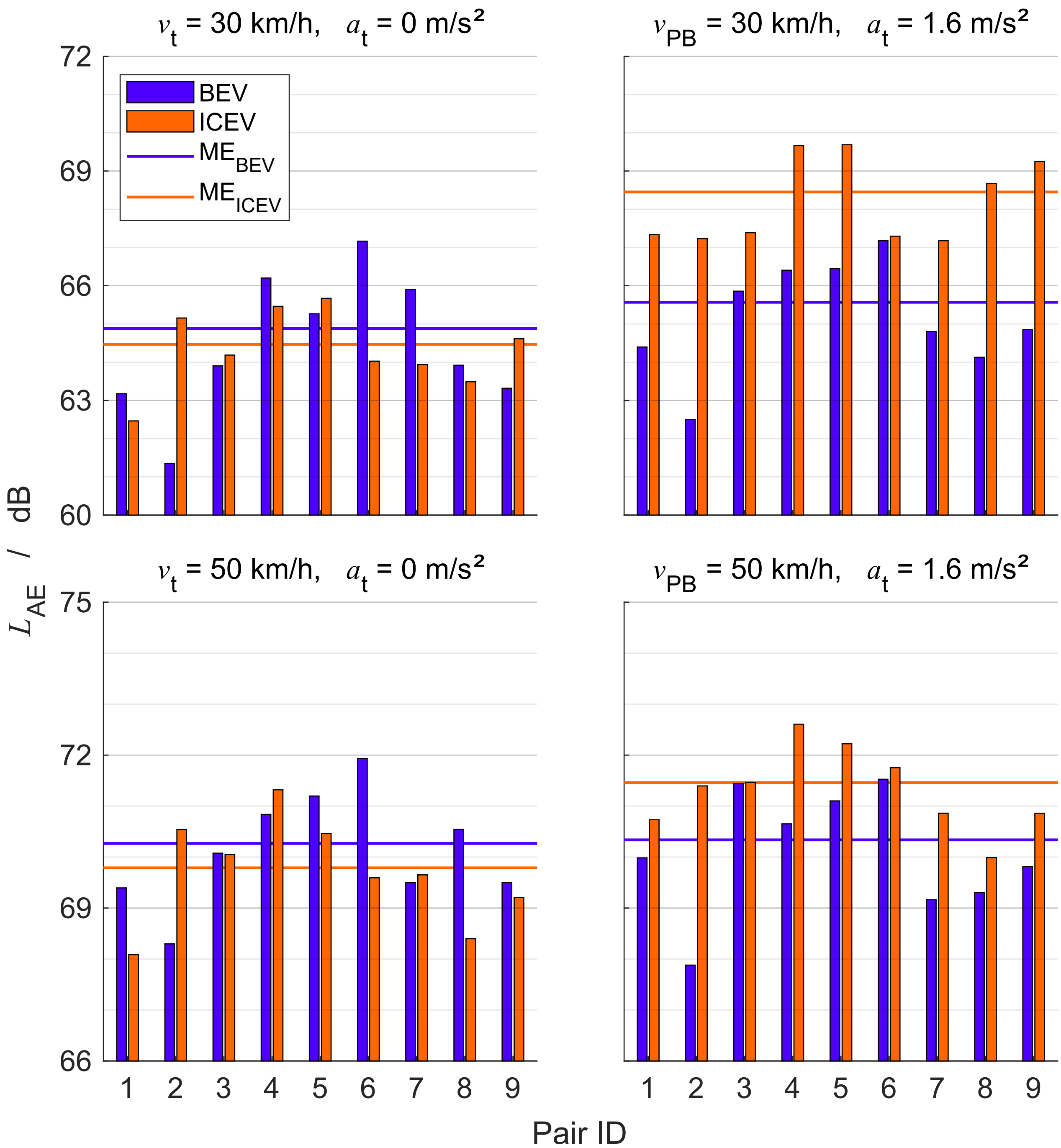

Figure 2. Mean pass-by energies of the 18 vehicles (bars). Each panel displays the levels at the respective driving profile with the target speeds and accelerations indicated above. The horizontal lines represent the mean energy (ME) over all BEVs (blue) and ICEVs (orange).

4.2 Vehicle-Specific Models for Pass-By Level Depending on Acceleration and Speed

From the measured triplets $[L_{\mathrm{AE}}, v_{\mathrm{PB}}, a_{\mathrm{PB}}]$, the pass-by level depending on speed and acceleration was modeled for each car individually. The parametric models are described by Eqn. (2), where the pass-by level L_{AE} is the variable depending on the measured acceleration a_{PB} and speed v_{PB} at the instance of pass-by.

$$L_{\mathrm{AE}}(a_{\mathrm{PB}}, v_{\mathrm{PB}}) = \left(\gamma_1 + \gamma_2 \cdot \left(\frac{a_{\mathrm{PB}}}{a_0}\right)^{\gamma_3} + \gamma_4 \cdot \left(\frac{v_{\mathrm{PB}}}{v_0}\right)^{\gamma_5}\right) \oplus \left(\delta_1 + \delta_2 \cdot \log_{10}\left(\frac{v_{\mathrm{PB}}}{v_0}\right)\right) \tag{2}$$

The reference acceleration and speed were set to $a_0 = 1\,\mathrm{m/s^2}$ and $v_0 = 30\,\mathrm{km/h}$. The $\oplus$ symbol represents energy summation. The seven coefficients γ_1, γ_2, γ_3, γ_4, γ_5, δ_1, and δ_2 were reasonably limited in range and then fitted (least squares algorithm) by the fmincon optimizer from the Global Optimization Toolbox for MATLAB [11]. With the found coefficient values, the average root mean square error $\overline{RMSE} = 0.6\,\mathrm{dB}$ over all individual models indicates a good fit of the models with the measured triplets.

The obtained models allow the vehicle-specific estimation of their pass-by levels for arbitrary speeds and accelerations within sensible limits to assess the pair-specific and average pass-by level differences $\Delta L_{\mathrm{AE}} = L_{\mathrm{AE,BEV}} - L_{\mathrm{AE,ICEV}}$ between the propulsion systems in various scenarios. Examples for these acceleration-dependent differences at pass-by speeds of 20 and 40 km/h are given in Fig. 3. Negative values indicate the potential of this BEV fleet to reduce the pass-by level compared to their ICEV counterparts.

4.3 Combining Models and Urban Driving

As an initial step towards assessing the acoustic differences between BEVs and ICEVs, the models described in Sec. 4.2 were applied to powertrain CAN bus data from 4000 km of urban driving by one plug-in hybrid car and one combustion engine car, both part of an institutional vehicle fleet accessible to a diverse group of drivers.

From this recorded driving data, probability densities of acceleration were derived in 2 km/h speed classes. The acceleration that is subceeded 95 % of the time (95th percentile, a_{95}) is shown in Fig. 4.

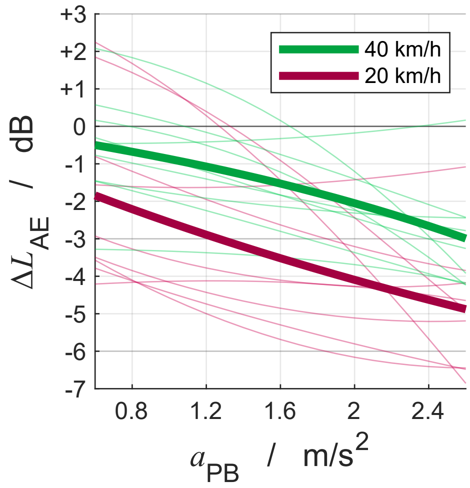

Figure 3. Modeled pass-by level differences $\Delta L_{\mathrm{AE}} = L_{\mathrm{AE,BEV}} - L_{\mathrm{AE,ICEV}}$ as a function of acceleration for two speeds following Eqn. (2). Thin lines represent individual vehicle pairs and thick lines the mean energy differences.

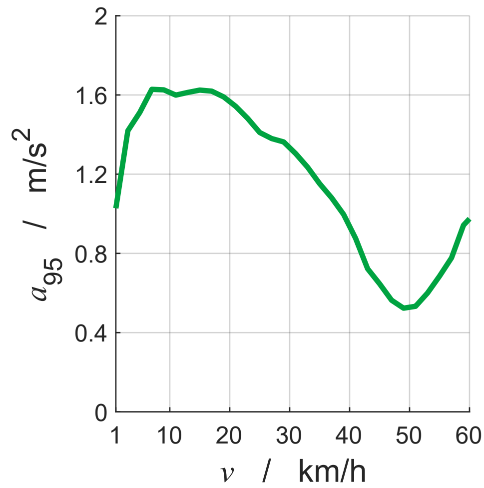

Figure 4. 95th percentile acceleration (a_{95}) of cars in real urban traffic depending on the driving speed.

Fig. 5 shows modeled pass-by levels L_{AE} of all BEVs and ICEVs, their ME, and the pair-wise ΔL_{AE} at constant speeds above 20 km/h and under the speed-dependent 95th percentile acceleration a_{95} in the whole speed range up to 60 km/h.

Both, the highest and lowest pass-by levels at constant speed are produced by BEVs spanning a range of 6 dB. Within the pairs, the speed-dependent ΔL_{AE}, that indicate the noise reduction potential of BEVs compared to the ICEVs, cover a range of ± 4 dB. Considering the ME, no noticeable difference is observed.

Regarding the high acceleration scenario, BEVs clearly produce less noise at speeds below 40 km/h. As indicated by the ΔL_{AE}, all BEVs show a noise reduction potential compared to the ICEVs at speeds below 20 km/h. The largest absolute difference of nearly 8 dB occurs below 10 km/h for vehicle pair #8. At these slow speeds, the average noise reduction potential at a_{95} amounts to 5 dB. However, the average difference decreases toward 40 km/h and remains negligible above this point.

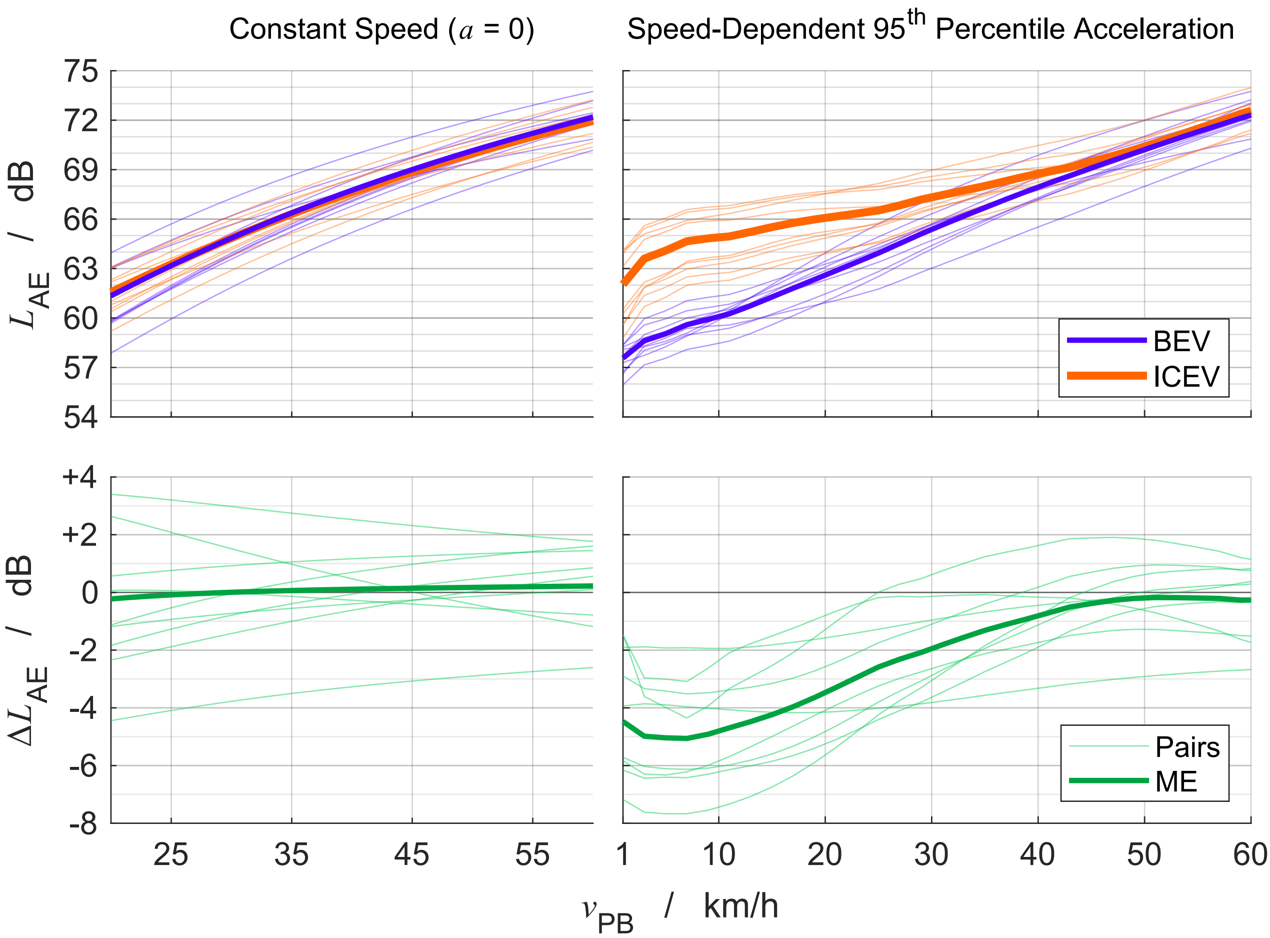

Figure 5. Modeled pass-by levels L_{AE} following Eqn. (2) (top) per vehicle (thin lines), the mean energies (thick lines) of BEVs (blue) and ICEVs (orange) and their differences $\Delta L_{AE} = L_{AE,BEV} - L_{AE,ICEV}$ (bottom) at constant pass-by speed (left) and under the speed-dependent 95th percentile acceleration a_{95} (right).

5. CONCLUSIONS

With the pass-by levels and kinematics collected in a measurement campaign with nine pairs of electric and comparable combustion engine cars, individual exterior noise models with speed and acceleration as input parameters were developed. These models allowed assessing the acoustical differences within the individual pairs and, on average, between the two propulsion concepts.

It was found that, for this particular fleet of vehicles, there is no level difference between BEVs and ICEVs at constant speed. However, under typical urban acceleration the BEVs have the potential to reduce pass-by levels by up to 5 dB at speeds below 10 km/h. This difference vanishes towards 40 km/h. Since above this speed tire noise presumably predominates over the propulsion noise, no notable differences between BEVs and ICEVs were found.

Further investigation in this ongoing study will consider the spectral differences between the propulsion systems and the influence of additional parameters such as tires, pavement and local kinematics in crossroad situations with unsteady traffic.

6. ACKNOWLEDGMENTS

We thankfully acknowledge all contributions from the colleagues involved at Empa and TCS in the project NE$\ddot{x}$US - **N**oise from **E**lectric vehicles under acceleration ($\ddot{x}$) in **U**rban **S**cenarios. Special thanks to Luca Steinmann for the dedicated work developing the on-board electronics and software that allowed the recording of kinematics and real-time evaluation of run validity.

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