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# DRIVEKUSTIK: ACOUSTIC DETECTABILITY OF ELECTRIC VEHICLES

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**Abstract:** *The project drivEkustik was funded from 2011 to 2013 by the Austrian Ministry for Transport, Innovation and Technology in order to analyse the impacts of the interior as well as the exterior acoustic emissions regarding to road safety. In work package 1, pass-by measurements based on aspects of the standard ISO 362 have been carried out to compare the sound emission of 4 different cars at a speed range between 10 and 50 km/h. All measurements were performed with conventional microphones and a binaural head. The binaural recordings were supplemented with recordings of different environments, in order to conduct a listening test to determine the acoustic detectability of the vehicles. Special attention was given to the assessment by visual impaired people, which are usually more affected by safety issues related with electric cars. For this reason, about 10% of a total of 105 participants were visual impaired people. A statistical analysis of the listening test with focus on the difference between the detection times was carried out. Furthermore, the stimuli of the listening test were analysed and compared with the detection time results of the listening test. In the present paper, the main results of this work are presented.*

Key words: electric vehicle, road safety, acoustic detectability

## 1. INTRODUCTION

Electric cars are one of the fastest growing groups of vehicles in the field of motorized individual transport. While the share of electric vehicles (EV) in the total vehicle stock of Austria in 2013 was only less than 0.1% [1], their percentage increase of 49% was the highest of all vehicle groups. Due to targeted promotion of alternative drive technologies in Austria, it is expected that the total number of EV will further grow over the next years, especially in urban areas where travel distances are usually shorter than in rural areas. An increasing electrification of the motorized individual transport offers a potential for noise reduction in urban road traffic due to the omission of the internal combustion engine noise.

Noise emitted by internal combustion engine (ICE) motor vehicles generally consists of 3 main components [2]. The speed-dependent tyre-road noise is caused by the interaction between the tyre and the surface of the road. The contribution of the drive system as second component to the overall noise plays usually an important role for speeds below 50 km/h and is mainly dependent on the rotational speed and the load of the engine. The third component comprises of noise caused by aerodynamic turbulences around the vehicle and becomes relevant at speeds above 120 km/h for cars. In case of EV, the noise of the drive system has very little influence on the overall noise due to its low acoustic emissions. Since the noise of the drive system is of vital importance for the acoustic detectability of vehicles at low speeds in traffic, EV can represent a higher risk from the acoustic point of view. The studies [3], [4] and [5] support this assumption for certain traffic situations, especially for speed ranges where the influence of the tyre-road noise is very low. However, specific results from [6] showed, that the acoustic detection of certain ICE-vehicles can be as difficult as for EV.

The project drivEkustik [7] was funded from 2011 to 2013 by the Austrian Ministry for Transport, Innovation and Technology (BMVIT) in order to analyse the driving behaviour and the acoustic perception of electric vehicles in relation to vehicles with an internal combustion engine regarding to the road safety of vulnerable road users. Special attention was given to visually impaired and blind people, which solely rely on their auditory perception to evaluate a traffic situation. While the scope of the project included the investigation of the exterior as well as the interior acoustic emissions of electric vehicles, this article deals only with the impacts of the exterior emissions, which were part of work package 1. Within this investigation, controlled pass-by situations of selected combustion engine and electric vehicles have been recorded and analysed. In order to compare their acoustic detectability, a listening test has been designed and conducted.

## 2. EXTERIOR NOISE EMISSIONS

One of the main goals of work package 1 within the project was the analysis of the exterior acoustic noise emissions of EV in comparison to the noise produced by ICE-vehicles. For this reason, several traffic situations have been recorded and analysed.

### 2.1. Traffic situations

According to the Austrian accident statistics of the Austrian Road Safety Board (KFV) in [7] from 2000 to 2012, a car colliding with a pedestrian appearing from the left or right side are the most frequent accident scenarios with the highest number of injured and deadly injured people. In order to investigate this traffic situation, pass-by measurements based on aspects of the standard ISO 362 have been conducted, as depicted in figure 1. In addition to a microphone at the conventional distance of 7.5 m from the center of the lane, a binaural head as well as a supplemental microphone were placed at a distance of 1.8 m to measure the noise emission at the position of an imaginary kerbside. The investigated speed range for this traffic situation was between 10 and 50 km/h. As primary measurement quantity, the maximum A-weighted sound pressure level $L_{AF,max}$ has been determined

$$L_{AF,max} = max(L_{AF}(t)) \quad (1)$$

The corresponding A-weighted sound pressure level envelope $L_{AF}(t)$ of a pass-by can be obtained by applying a exponential time weighting with the time constant $\tau = 125ms$ on the A-weighted sound pressure envelope $p_A$

$$L_{AF}(t) = 20log_{10}\left(\frac{\sqrt{\frac{1}{\tau}\int_{-\infty}^{t} p_A^2(\xi)e^{-(t-\xi)/\tau}d\xi}}{p_0}\right) \quad (2)$$

Both traffic situations have been recorded for 4 different vehicles: an electric city car, an electric compact car, an ICE mini van as well as an ICE SUV.

### 2.2. Measurement results and analysis

The results of the 4 different investigated vehicles are depicted in figure 2. Due to the small tyre dimensions and the electric engine, the maximum pass-by level of the electric city car is significantly lower than all other investigated vehicles from 10 km/h to 50 km/h. The result of the electric compact car for 10 km/h at 1.8 m is very close to the electric city car, but with increasing speed, the influence of the

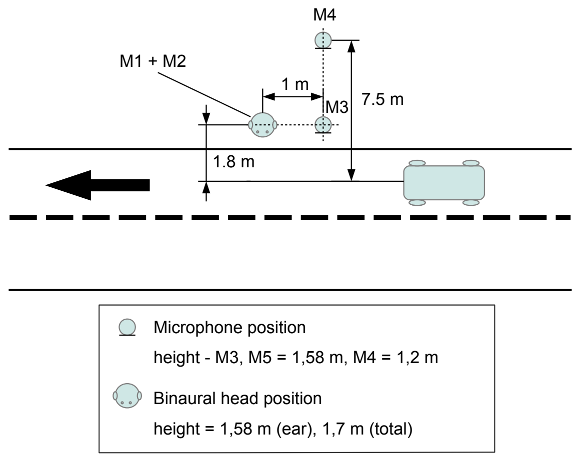


**Figure 1:** measurement setup for the investigated traffic scenarios of a pass-by situation

tyre-road noise leads to a higher maximum pass-by level due to the larger tyre dimensions. For speeds of 40 km/h and more, the maximum pass-by level of the electric compact car is very similar to the values of the investigated ICE-vehicles. The large difference of about 20.0 dB(A) between the ICE mini van and the electric cars can be attributed to the high age of the ICE-vehicle.

Although the results in 7.5 m are of limited relevance for a situation where a pedestrian stands on the kerbside of the street, it is interesting that the maximum pass-by level of the electric compact car is very similar to the level of the ICE-vehicles for speeds of 20 km/h and more. At 40 km/h, the maximum pass-by level of the electric compact car is even the highest of all.

## 3. ACOUSTIC DETECTABILITY

### 3.1. Experimental design

For determining and comparing the acoustic detectability of EV with the one of ICE vehicles, a listening test has been designed and conducted within this project. Every stimulus for this test was created from one of the binaural vehicle recordings of the investigated traffic situations and was furthermore superimposed with an additional binaural background noise recording, in order to acoustically simulate typical urban environments. The task given to the participants was to release a trigger, when they have detected the approaching vehicle. Figure 3 visualizes the process of playing back a stimulus and releasing the trigger.

The Stimuli of the listening test included one EV (city car) and one ICE-vehicle (SUV) for constant speeds at 10, 20 and 30 km/h supplemented with 3 different background recordings: a rural back-road, a suburban back-road and an urban back-road. For the rural back-road, no additional recordings were made since this background noise was part of the vehicle recordings. Table 1 shows some acoustic information

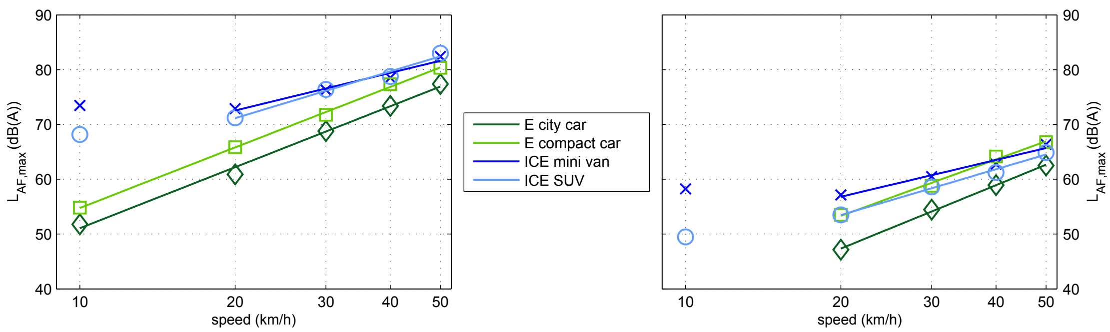


**Figure 2:** maximum pass-by level at constant speeds, measured with the binaural head (built-in microphone, which was facing the approaching vehicle) at a height of 1.58 m in 1.8 m distance (left) and with a microphone at a height of 1.2 m in a distance of 7.5 m (right). At 7.5 m and a speed of 10 km/h, the difference between the background noise and the emitted noise of the EV was to small to determine a maximum pass-by level. Due to the very dominant and rotational-speed-dependent influence of the combustion engine noise below 20 km/h, the determined logarithmic regression function for the ICE-vehicles starts at 20 km/h.

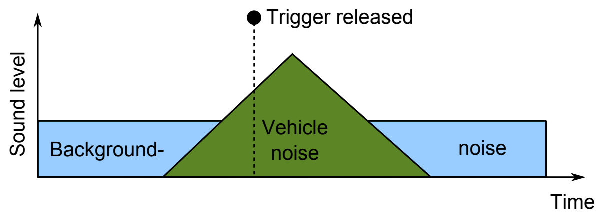


**Figure 3:** Schematic temporal envelope of a stimulus with a pass-by traffic situation. The vertical dashed line with the dot represents an exemplary point, where a participant has released the trigger.

about the three different background environments for the pass-by situation.

In order to obtain a statistically meaningful result, a total of 105 participants were recruited, including 14 visually impaired and blind people. At the time of the listening test, 55% of the participants were younger than 31, while the age of 30% was between 31 and 45 years. The remaining 15% were people with an age above 45 years.

All participants were confronted with the stimuli via headphones via a calibrated playback system to maintain the original levels of the recordings. In addition, the following three aspects have been considered for the listening test:

- For the pass-by situation, the driving direction (from left to right or the other way around) of the approaching car was chosen randomly for every stimulus.
- Vehicle and background recording were combined in such a way, that the first possible detection time is different from stimulus to stimulus in order to prevent the participant from releasing the trigger by guessing after a certain period of time.
- The participants were asked to stand during the listening since they would have stood also in a real-life traffic situation.

Furthermore, a group of stimuli with the same background noise was played in a randomized sequence at the listening test. The order of the stimuli groups was randomized too. With an introduction in the beginning and a short questionnaire in the end, the listening test lasted 30 minutes in total.

**Table 1:** Energy equivalent continuous sound level $L_{A,eq}$ of the recorded environments.

| *environment* | $L_{A,eq}$ |
|---|---|
| rural back-road | 45.0 dB(A) |
| suburban back-road | 55.6 dB(A) |
| urban back-road | 60.0 dB(A) |

### 3.2. Listening test results

The results of the listening test can be presented in two different forms - as remaining time (detection time), or as remaining distance (detection distance), before the approaching vehicle would have reached the participant (crossing point). A graphic visualization of the detection distances of all pass-by results is shown in figure 4. In addition, a stopping distance $s_s$ is assumed according to

$$s_s = vt + \frac{v^2}{2a} \quad (3)$$

whereat $v$ represents the vehicle speed and $a$ the braking deceleration, which has been set to 8 $m/s^2$ as in [6]. By assuming an average reaction time of the driver with $t = 1$ s, the stopping distances for 10, 20 and 30 km/h equal to 3.26 m, 7.48 m and 12.67 m. Further considerations about the driver reaction time in general can be found in [8]. The stopping distance has been taken into account at the point, where 75% of all participants had detected the vehicle (equals to the 25% quartile) and under the assumption that the remaining participants would cross the street without noticing the vehicle.

If not otherwise mentioned, at this point all detection distance results within the text are considered as median values of all results for one single traffic situation. For the best-case constant pass-by situation with the background noise of a rural back-road (figure 4 - left), the investigated EV has smaller detection distances and therefore has been detected later at all speeds as the investigated ICE-vehicle. The high detection distance difference of 27.7 m can be traced back to the very easy detectable sound of the combustion engine of the ICE-vehicle. The very low difference of 8.6 m at a constant speed of 20 km/h is connected to the proportionately low rotational speed of the combustion engine in the $2^{nd}$ gear and to the increasing influence of the tyre-road noise on the detectability. For a speed of 30 km/h, the difference equals to 18.5 m.

Beside the traffic situations with the lowest background noise, the traffic situations with the highest background noise of an urban back-road will be analysed (figure 4 - right). While all participants have detected the vehicle before the crossing point (CP) for scenarios with the rural background noise, the results for the urban back-road draw a different picture. For the EV with 10 km/h as worst-case traffic scenario of the whole listening test, 31 % of all participant didn't release the trigger at all. For the remaining 69 %, about half of the participants released the trigger, after the EV had already reached the crossing point. For a constant speed of 20 km/h, the situation improves to a detection rate of 98 %. However, the median of the detection distance of 6.9 m is very close to the crossing point. If the 25 % quartile is taken into account, the assumed stopping distance of 7.48 m would not be sufficient if the participant does not notice the vehicle and would cross the street. The detection distances of the investigated ICE-vehicle are for all speeds lower than for the same traffic situations with the background noise of the rural back-road. Nevertheless, even at the 25 % quartiles in combination with the assumed stopping distances, there is still a remaining distance to the crossing point. A summary of differences between the investigated EV and the investigated ICE-vehicle can be found in table 2.

A further focus within the scope of the listening test was on visually impaired and blind people. Although the average age of the visual impaired people was higher than the average age of the rest of the participants, no significant difference of the detection times could be found. Table 3 even points out, that in the worst-case scenario with the EV at 10 km/h in urban background noise the visual impaired participants detected the EV 1.6 seconds earlier than the sighted participants.

### 3.3. Causes of detectability

Beside the question when or at which distance a vehicle can be detected, the causes of the detection were one further aspect of the investigation.

Therefore, the detection times of specific stimuli have been analysed together with its spectrogram and its sound pressure level. The comparison of the investigated EV at a constant speed of 20 km/h with the investigated ICE-vehicle at the same speed in figure 5 shows, that the components responsible for the acoustic detectability are clearly identifiable in a low background noise of a rural back-road. As soon as the ICE-vehicle has been detected by the first person at second 4.9 (start of the detection time distribution), the spectrogram of the channel with the approaching vehicle shows two rises - in the frequency region between 40 and 50 Hz and in the area between 1 and 2 kHz. While the lower rise can be traced back to the lower orders of the combustion engine, the maximum between 1 and 2 kHz is connected to the tyre-road noise of the vehicle. Furthermore, these two components are responsible for the rise of the overall sound pressure level in the right channel of the stimulus. Due to obvious reasons, the spectral influence of the combustion engine is not present for the EV at a speed of 20 km/h. Since this vehicle has been detected by the first participant at second 6.5, it can be assumed, that the missing engine noise has an impact on the acoustic detectability of the vehicle.

## 4. SUMMARY AND CONCLUSIONS

An increasing electrification of the motorized individual transport offers a potential for noise reduction in urban road traffic due to the omission of the internal combustion engine noise. Regarding to road safety, the missing noise from the combustion engine can lead to a higher risk in certain traffic situations from the acoustic point of view. This can be especially critical for visually impaired and blind traffic participants, since they solely rely on their auditory perception to evaluate a traffic situation.

The project drivEkustik investigated the impacts of the noise emissions of electric vehicles regarding to road safety. Within work package 1 of the project, constant pass-by measurements have been carried out with different electric vehicles and combustion engine vehicles in order to compare the typical sound emissions of these two different vehicle groups. Furthermore, a listening test has been conducted for determining the acoustic detectability of electric vehicles in comparison to combustion engine vehicles.

The results of the acoustic measurements of the pass-by scenario show significantly lower maximum levels for the investigated electric vehicles in comparison to the investigated combustion engine vehicles at a speed of 10 km/h. This difference decreases with increasing pass-by speed due to the influence of the tyre-road noise.

The analysis of the results of the listening test conducted within this study shows pretty clear, that the investigated electric vehicle will be detected later than the investigated combustion engine vehicle, if traffic situation and the background noise are similar for both type of cars. It can be assumed, that this statement also applies to other types of electric and conventional cars, especially at very low speeds. Nevertheless, it must be noted that the acoustic detectability of a vehicle is influenced by the type of the installed engine

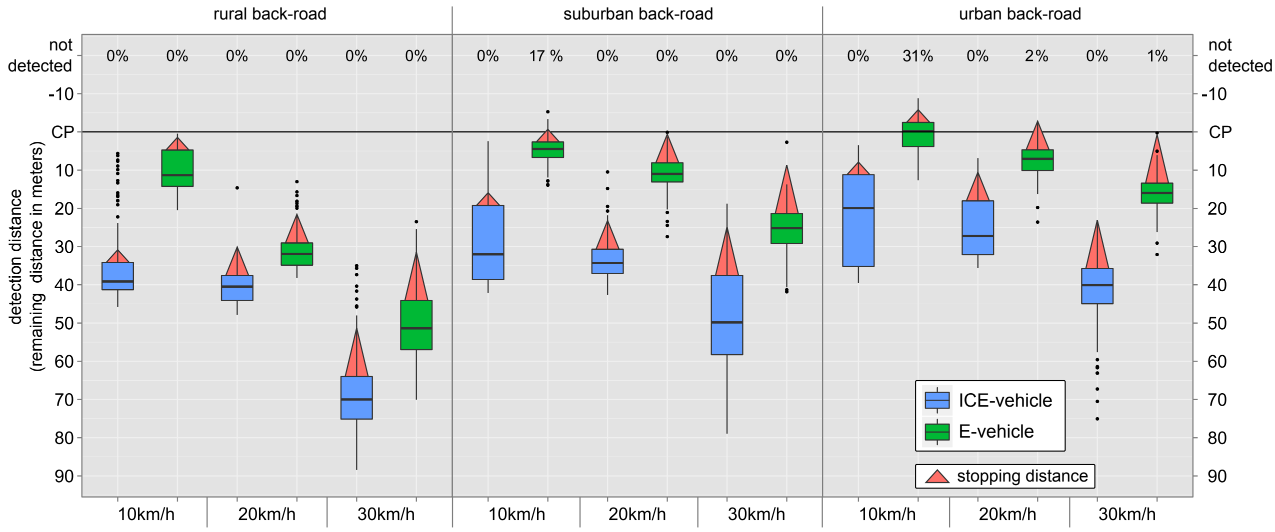


**Figure 4:** Listening test results for the investigated pass-by traffic situation at different constant speeds with the background noise of a rural back-road (left), a suburban back-road (center) and urban back-road (right). The detection distances for every stimulus are represented as a box plot. The box area of the box plot (green/blue) limited by the 25% and 75% quartile and contains the median value. Depending on the constant speed, the assumed stopping distance (red) has a different length and is depicted above the 25% quartile. Regions of the box plot over the black horizontal line of the crossing point (CP) represent participants, who had released the trigger at a point, after the approaching vehicle would have reached the participant. The upper end of the vertical axis of every stimulus contains the percentage of participants, who didn't release the trigger at all.

**Table 2:** Detection time and detection distance differences between the investigated ICE-vehicle and the investigated EV. All quantities are based on the median values.

| *constant pass-by speed* | rural back-road | suburban back-road | urban back-road |
|---|---|---|---|
| 10 km/h | 10.0 s / 27.7 m | 9.8 s / 27.2 m | 7.2 s / 20.1 m |
| 20 km/h | 1.5 s / 8.6 m | 4.2 s / 23.4 m | 3.6 s / 20.0 m |
| 30 km/h | 2.2 s / 18.5 m | 2.9 s / 24.6 m | 2.9 s / 24.1 m |

**Table 3:** Detection time differences between sighted and visually impaired and blind participants. All quantities are based on the median values. Negative values denote an earlier the detection by the visually impaired and blind participants

| *constant pass-by speed* | ICE-V rural back-road | EV rural back-road | ICE-V suburban back-road | EV sub-urban back-road | ICE-V urban back-road | EV urban back-road |
|---|---|---|---|---|---|---|
| 10 km/h | -0.3 s | 2.1 s | 1.1 s | 0.0 s | -0.1 s | -1.6 s |
| 20 km/h | 0.2 s | 0.0 s | 0.0 s | 0.2 s | 0.3 s | 0.2 s |
| 30 km/h | 0.2 s | -0.2 s | -0.4 s | 0.0 s | 0.0 s | -0.1 s |

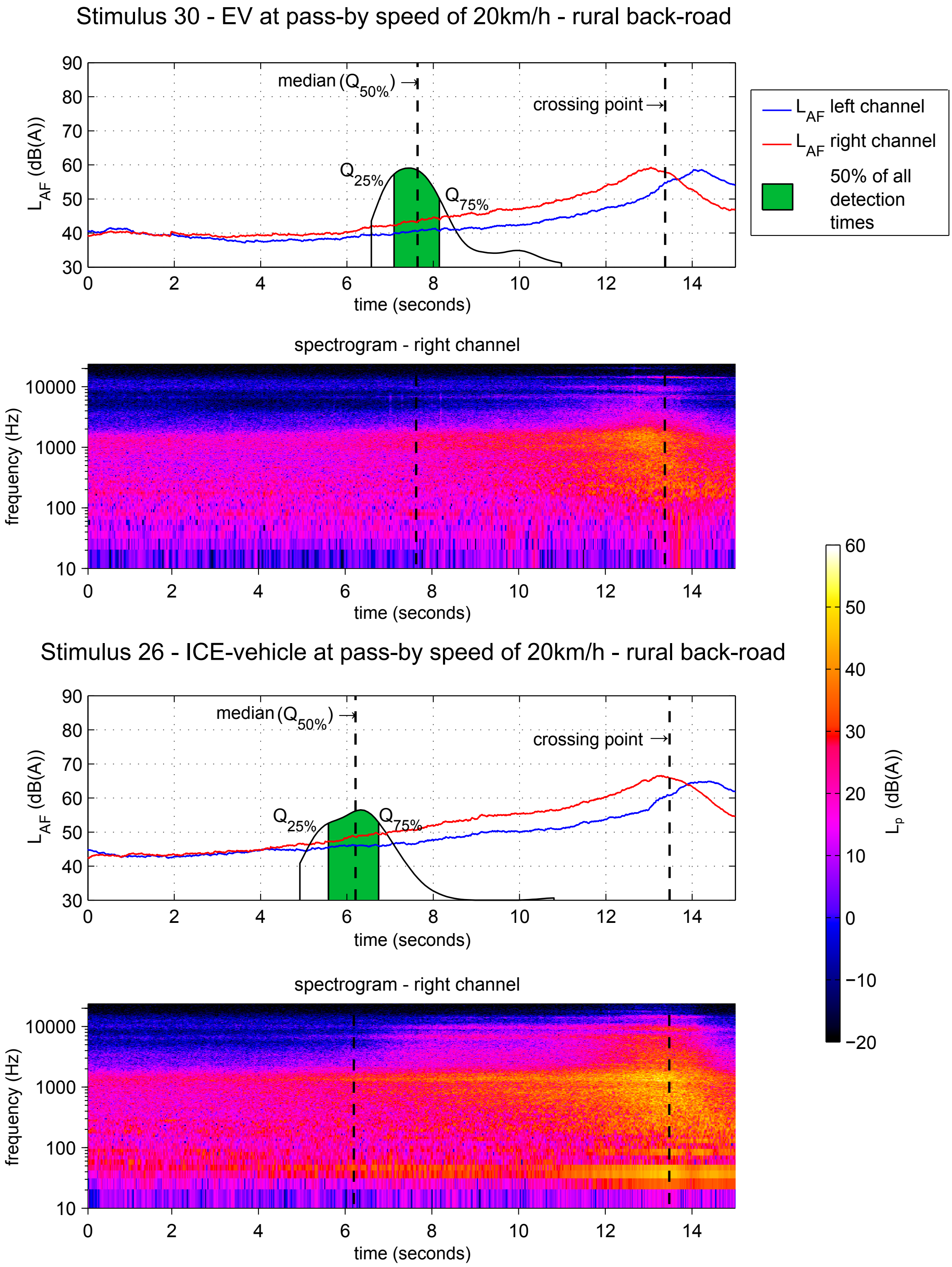


**Figure 5:** Comparison between two stimuli of the listening test. The respective upper plot of every stimulus contains the fast-weighted, A-weighted sound pressure level of the left (blue) and right (red) channel, as well as the normalized kernel density estimation of the detection time distribution (black with green coloured area) of all participants. The median value of the detection times and the crossing point of where the vehicle would have reached the participant are display as vertical dashed black lines. The respective lower plot of every stimulus shows the spectrogram of the channel with the approaching vehicle.

as well as by the overall acoustic design of the vehicle. Results from [6] pointed out, that a luxury ICE family car was detected later than the investigated electric compact car for a constant pass-by scenario at 20 km/h. Furthermore, a significant impact of the background noise could be proven, especially for the investigated electric vehicle. In the worst-case scenario with high urban background noise at a constant speed of 10 km/h, the emitted noise of the electric vehicle is strongly masked and about two thirds of the participants couldn't detect the vehicle at all or at a point, where it had already passed the position of the participant.

The comparison between the results of sighted and visual impaired participants of the listening test shows no significant difference, whereat the sample was different with 91 sighted and 14 visual impaired people.

**Acknowledgement**

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## REFERENCES

[1] **Stock of Motor Vehicles and Trailers**, Austrian stock of vehicles in 2013 from: `http://www.statistik.at/web_en/statistics/transport/road/stock_of_motor_vehicles_and_trailers/index.html`, Statistics Austria, 2014

[2] U. Sandberg, J. A. Ejsmont: **Tyre/road noise reference book**, Informex Ejsmont & Sandberg Handelsbolag, Sweden, 2002.

[3] L. Garay-Vega, A. Hastings: **Quieter cars and the safety of blind pedestrians: phase I**, NHTSA, USA, 2010.

[4] E. Altinsoy: **The detectability of conventional, hybrid and electric vehicle sounds by sighted, visually impaired and blind pedestrians**, Proceedings of the 42$^{nd}$ Internoise, Innsbruck, 2013.

[5] P. Morgan, L. Morris: **Assessing the perceived safety risk from quiet electric and hybrid vehicles to vision-impaired pedestrians**, TRL Published Project Report PPR525.

[6] K. Glaeser, T. Marx: **Testing the Sound Detection of Electric Vehicles by Blind or Visually Impaired Persons**, Proceedings of the 7$^{th}$ Forum Acusticum, Krakow, 2014.

[7] M. Pilgerstorfer, M. Conter: **Fahrverhalten in und akustische Wahrnehmung von Elektrofahrzeugen**, Forschungsarbeiten des Österreichischen Verkehrssicherheitsfonds, Issue No. 27, Vienna, 2013.

[8] ISO 362-1:2007, **Measurement of noise emitted by accelerating road vehicles**.

[9] S. Kerber: **Wahrnehmung von Fahrzeugaußengeräuschen in Hintergrundgeräuschen: Psychoakustische Beurteilungen und modellbasierte Prognosen**, Dissertation, Technical University of Munich, 2008.