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A detailed investigation on three-dimensional sound emittance of today’s motorised vehicles in urban contexts

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Abstract
Nowadays, the sound emissions of most machines and vehicles have to be recorded before the product is launched and are subject to individual limit values. Numerous product-specific measurement regulations exist for this purpose, which should allow users to compare the respective products with each other. However, it is generally not possible to derive the noise exposure for a resident from this. For that, it would be necessary to know both the spatial distribution of the radiated sound and the sound field with its boundary surfaces and sinks. In an interdisciplinary and interdepartmental research project at Frankfurt UAS, noise sources are currently being investigated in the context of urban development, reflecting facades, and absorbing green spaces. A detailed investigation on three-dimensional sound emittance of motorised vehicles will be carried out as well as absorption and reflection measurements in representative metropolitan areas. Using these results, it will be possible to define the individual effect of single noise sources on specific receiver positions in an urban setup.

Keywords: urban acoustic; polar pattern; electric car; road traffic; sound prediction

1 Introduction

In addition to the reflection and absorption properties of inner-city buildings, it is above all the emission behaviour of passing motor vehicles that determines noise pollution in metroplitan areas. Several studies have been carried out throughout the years to determine the noise emittance of vehicles to be used as input data in noise propagation calculations. Among others, the Parkplatzlärmstudie 6. Edition (Recommendations for the calculation of noise emissions of parking spaces, motorway services, bus stations, parking garages, and underground parking spaces) [1] from 2007 or the research project from 2020 “Überprüfung der Geräuschemissionen von Motorrädern im Straßenverkehr” (review of noise emissions of motorcycles in present road traffic) [2] from the German Environment Agency can be named. Because of its strong relation to noise propagation calculations all these studies investigated the noise emission in relation to the normative fixed street level positions 1.2 m above ground in 7.5 m distance to the object. The research project “Bestimmung der vertikalen Richtcharakteristik der Schallausbreitung von Pkw, Transportern und Lkw” (Determination of the vertical directivity of noise emission of cars, vans and trucks) [3] commissioned by the Federal Highway Research Institute (BAST) in 2009 extended the view on noise emission of cars to the vertical dimension. Based on results of on-site measurements of controlled pass-by cars the study concludes that the angle of maximum noise emittance varies in the range of the investigated cars, vans and trucks. The basic simplification made for noise propagation that cars emit the maximum noise level at one specific angle has to be reconsidered. For the automobile industry and production, the noise emittance of cars is limited by technical rules and controlled by European guidelines such as 70/157/EWG [4] in conjunction with specific measurement procedures such as DIN ISO 361 Part 1 [5]. The homologation of cars in combination with noise propagation methods based thereon should prevent complaints. This, however, is not reflected in reality. Even though the car as a noise source seems to be precisely documented and controlled in production and usage, the number of noise-related complaints is still increasing, especially by residents in metropolitan areas as documented in the many reports. Among others the report from the European Environment Agency: “Healthy environment, healthy lives: how the environment influences health and well-being in Europe” [6] or the national report from the German Environment Agency: “status of noise nuisance in Germany” [7] can be listed. This is even more remarkable as metropolitan areas consist of highly regulated land usage planned and controlled by local authorities while considering the measure of noise propagation calculations. To enhance the knowledge about the acoustic properties of vehicles in urban contexts the acoustic measurements described in this article were conducted as a part of the ongoing interdepartmental research project at the Frankfurt University of Applied Sciences: “Development of an urban planning parameter for acoustically effective building construction” funded by the Federal Ministry of the Interior, Building and Community. The attempt was made to document under controlled conditions the noise emission of cars and a motorcycle driving at constant speed in a range 180° above the street around the car perpendicular to the driving direction on an abandoned airfield. The measurements excluded vans and trucks to focus on cars with various engine types. This should represent the most current noise source in urban spaces, the car and its ongoing modifications from a combustion engine driven to alternative engine concepts. It is believed that the results presented here will lead to a more specific way of noise prediction in urban contexts.

2 Measurement setup

2.1 Measuring environment

The acoustical investigation of the vehicles was performed at the abandoned August Euler airfield in Griesheim, close to Darmstadt (Germany). The sealed surfaces of the former airfield are used as a test field for driving or for flight experiments under administration of the Universities of the Hessian State. The surrounding grass land is protected by nature conservation and offer ideal free field conditions. Figure 1 shows the asphalted flight path of 20 m width and 1160 m length.

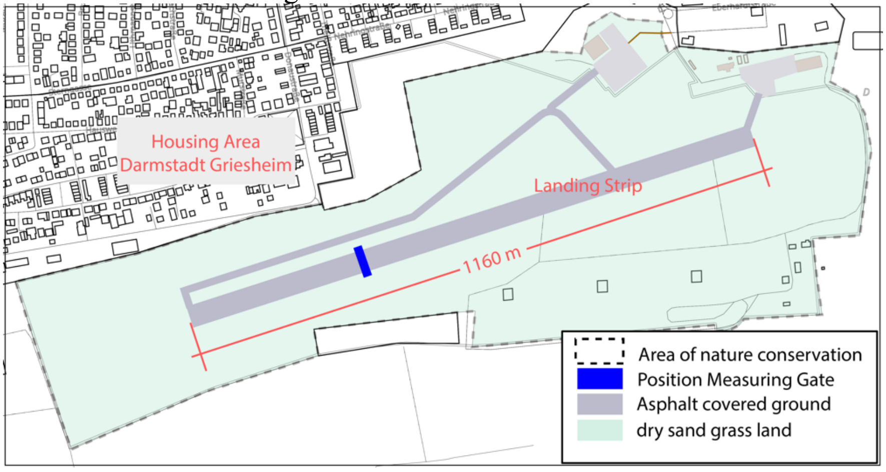

Figure 1 – Map of August Euler airfield in Griesheim, close to Darmstadt, Germany, Drawing based on open-source street map, no scale

2.2 Test Vehicles

Four different vehicle types with different drive systems were chosen to represent the common drive technologies within this acoustical test setup. These include two standard small cars, one with an electric drive and one with a petrol engine. The electric car used was only equipped with an electric drive. It had no auxiliary power units like a range extender engine. The third one, a diesel-powered car, is a standard estate car. The fourth vehicle, a motorbike, has a petrol-powered Boxer engine and represents the group of two-wheel vehicles. The key figures of the vehicles can be found in Table 1.

Table 1 – Key figures of the Vehicles

Vehicle	Drive system	Weight [Kg]	Year of Production
Standard small car	electric	1345	2016
Standard estate car	diesel	1564	2005
Standard small car	gasoline	1199	2016
motorcycle	gasoline	246	1993

2.3 Measuring Setup

Based on DIN ISO 361-1 two microphones were installed at 7.5 m distance from the centre of the roadway and at 1,2 m height. In the following these are called the norm positions “Ref L” and “Ref R”. A semi-circular arch with a radius of 4,5 m made of segmented plastic pipes – the measuring gate – was erected centrally above the roadway. Seven microphones were positioned on the measuring gate so that they were evenly distributed across the arch. The two lowest microphones were palced at the height of the straight line between the centre of the roadway and the norm position. In the following the seven measuring positions attached to the measuring gate are named according to their angles: e.g. “Position 36°”. This setup was developed based on the guideline 70/157/EWG [4]. Figure 2 shows the measuring setup with the microphone positions.

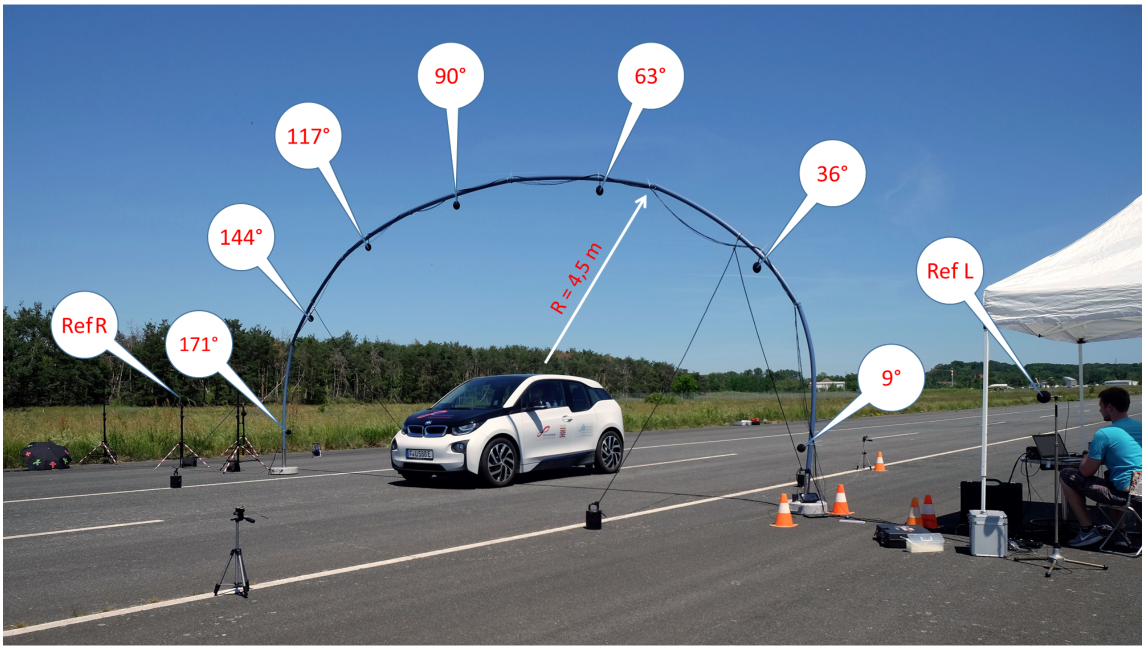

Figure 2 – The measuring gate with seven microphone positions attached to it, positioned on the landing track of the abandoned airfield with the standard small car with electric drive under measurement. The positions Ref L and Ref R are set to the position which are defined by the DIN ISO 361-1 [5]

2.4 Performance of the measurements

For the tests, the cars were measured while driving at a constant speed. The speed was increased from 10 km/h to 120 km/h in steps of 10 km/h. To ensure the exact speed, the driver drove GPS supported, and compliance with the speed was ensured by using light barriers. In each case an appropriate gear was chosen for the respective speed. In addition, the vehicles drove through the measuring gate once each from both directions. Pass-bys with faulty speed meter readings were repeated. This resulted in at least 24 measurement sequences per vehicle.
Data acquisition was realised using a compact 24 channel frontend. The measurements were carried out with a total of nine Class1 microphones. At the beginning of the measurements, all microphones were calibrated. A single uninterrupted 10 channel recording (incl. trigger channel of the light barrier) was made for all pass-bys. Additionally, annotations were spoken into a separate microphone. Light barriers were installed 10 m in front of and behind the measuring gate. These recorded the velocities at which the vehicle entered and exited the measuring space. The uninterrupted recording of all pass-by events enables the determination of the precise background noise of the measuring site in the intervals between pass-by sequences. The detected level for the background noise was in the range of 37 dB(A) to 39 dB(A). The driving direction from West to East was with a headwind. The driving direction East to West was a downwind condition. During the day of the measurements a light wind of a nearly constant velocity of 4 m/s was documented. For the here presented analysis the recordings of the downwind driving direction East to West were used because these data represent pass-bys for specific cars at different speeds under equal downwind conditions. The recorded data were analysed using a post processing software based on the digitalised time signal. The software outputs the A- and F-weighted level vs. time curve. These were exported to Excel spreadsheets. Based on the triggers, the individual pass-by events could be identified within the entire measurement file.

3 Results of the measurement

The analysis was executed stepwise. In the first step all single pass-by sequences were extracted. With the recorded triggers the zero position of the measuring gate on the timeline was identified. Around the zero position an interval with a duration of 3 s was selected for the further data analysis. The 3 s intervals were the basis for calculating the level over time diagrams and the calculation of the equivalent continuous noise level LEQ for each 3 s sequence. In addition, LAF levels for pass-by sequences were determined according to the procedure described in DIN ISO 361-1 [5].

3.1 Analysis of vertical sound radiation based on LAF Levels

To obtain insight on the normative regulated determination of sound emissions from vehicles the data set was analyzed using methods inspired by DIN ISO 361-1 [5]. The maximum level within the measurement interval of 3 s is determined. The polar plots show these maximum recorded levels at specific microphone positions during pass-by events at the driving speeds ranging from 20 km/h to 120 km/h. The horizontal bar graphs below the symbol of the car are representing the maximum detected level within the measurement interval of 3 s at the norm positions “Ref L” and “Ref R”.

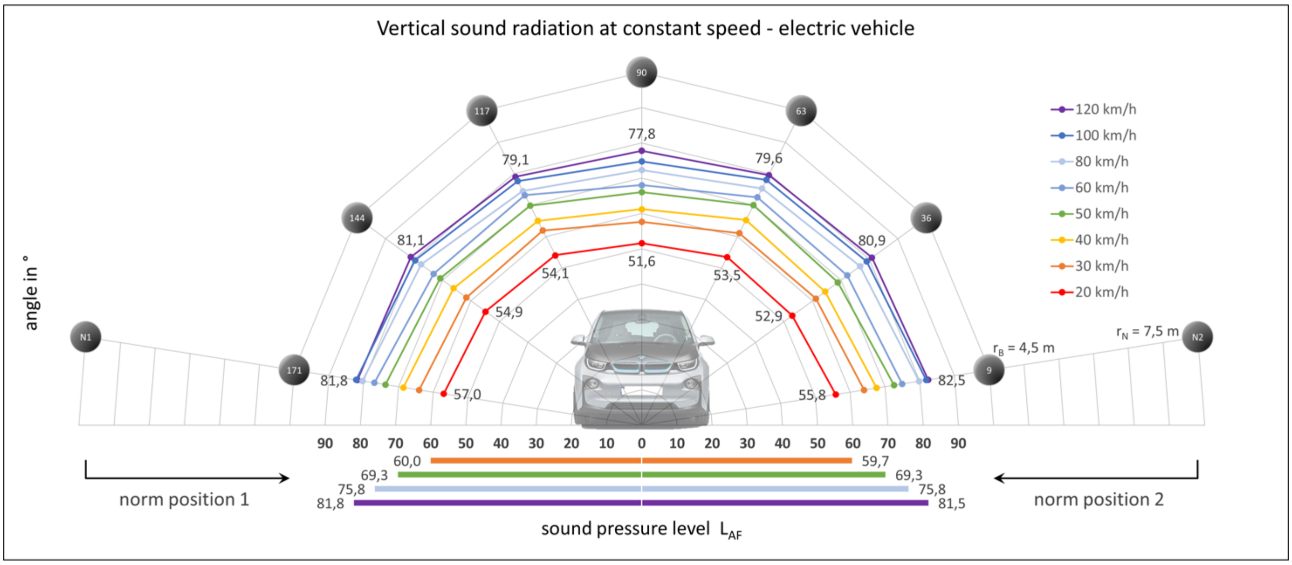

Figure 3 – Polar plot of the electric driven standard small car

The results for the electric driven standard small car range from the minimum value of 51,6 dB(A) at 20 km/h at Position 90° to 82,5 dB(A) at 120 km/h at Position 9°. It can be seen in Figure 3 that with increasing speed the vertical sound radiation slightly changes.

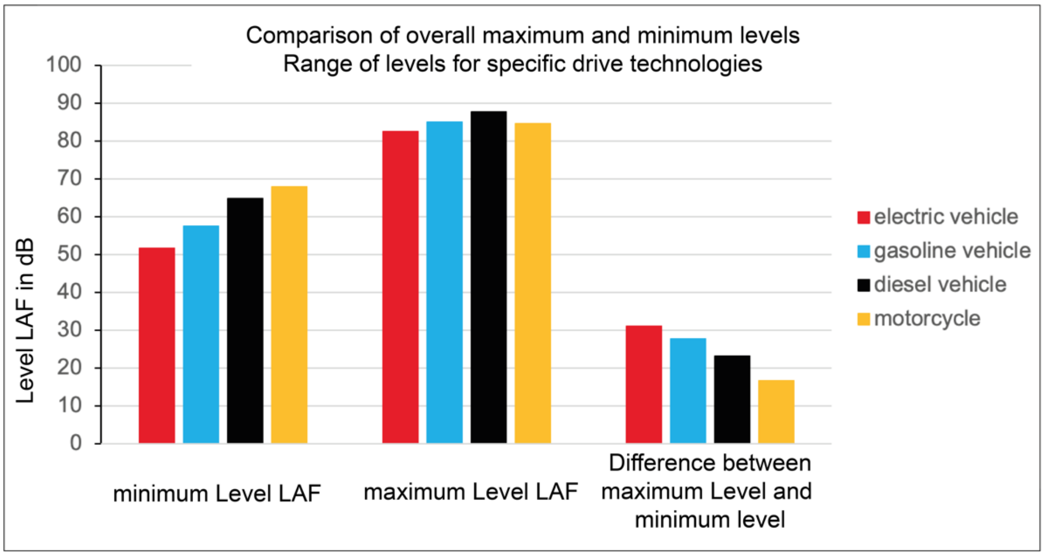

Figure 4 – Comparison of the loudest car under measurement the diesel car with the silent electric car. The LEQ values calculated out of the 3 s intervals recorded in Position 9° and Position 90° are shown

Figure 4 provides a sequence based on LAF values. Therein the electric car marks the low end in all driven speeds. At the top end of the sequence, we see the diesel engine with a maximum level of 87.7 dB(A) at 120 km/h in Position 9°, which is 5.2 dB over the value 82.5 dB(A) at 120 km/h in Position 9° for the electric driven standard small car. Figure 4 clearly illustrates the interdependence between the type of engine in the cars and the emitted sound. As this maximum level detection method does not provide any deeper insight further analyses were carried out. In the following investigation the difference of levels between Position 9° and 90° was used to identify significant changes in the sound radiation in relation to the position of the driving vehicle.

3.2 Analysis of sound radiation vs. time

The level vs. time diagrams show the recorded LAF levels at specific microphone positions during pass-by sequences at different driving speeds. Figure 5 and Figure 6 show a comparison of the electric driven car with the diesel car.

In Figure 5 the courses of levels are shown which represent the typical inner city speed limit of 50 km/h. The course of levels at Positions 9°, 36°, 63°, 90 °for the electric car appear equivalent to an ideal pass-by of a point source. Around the origin in the graph at position 9° the course of the levels of the electric car shows a dip. This marking the point where the body of the electric car partly shadows some of the tire related noise sources. While the diesel car shows the same dip at the origin the broader course of levels between zero and 13.9 m represents the noise from the exhaust pipe.

In Figure 6 the courses of levels graphs are shown. These represent the typical speed limit of 100 km/h for country roads in Germany. The course of levels at position 9° for the electric car appears equivalent to an ideal pass-by of a point source. The dip at the origin also appears, but, due to relation to the higher speed, it is not as distinct.

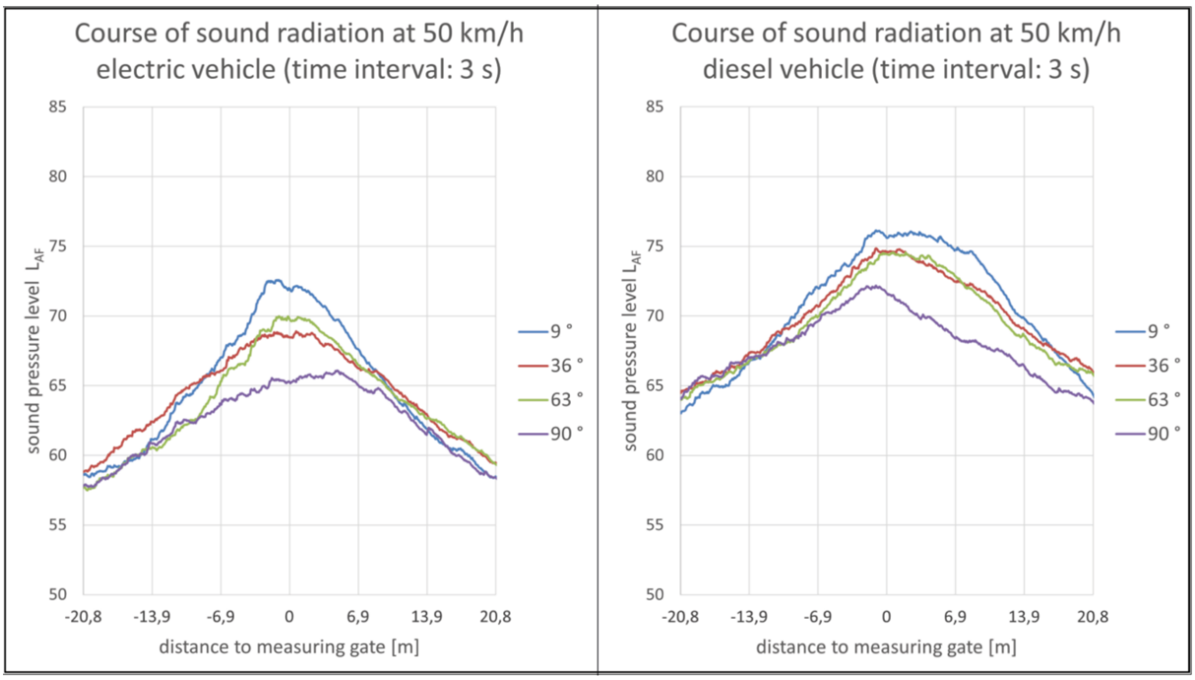

Figure 5 – Level vs Time for the electric driven car and the diesel car at 50 km/h

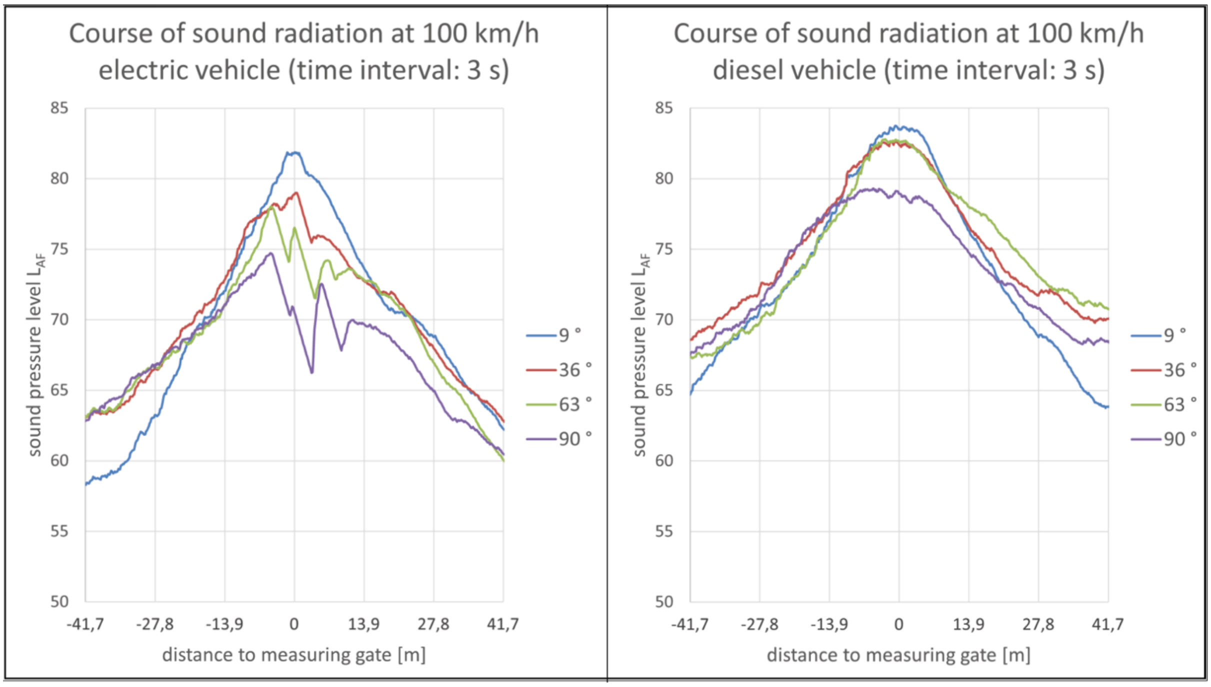

Figure 6 – Level vs Time for the electric driven car and the diesel car at 100 km/h

The effect where the body of the electric car partiallyshadows some of the tire noise sources is even more apparent in the graphs for positions 36°, 63°, and 90°. The sudden changes of level within the range of 7.5 dB represent the shadowing of the tire noise sources by the body of the car.

At 100 km/h the diesel car does not show this dip at the origin. The broader course of levels caused by the diesel engine and the exhaust pipe can be noticed. Noticeably, at the point of entry at -41.7 m the level at position 9° is lower than the level at position 90° for both vehicles. For the electric car this more distinct than for the diesel car. At -41.7 m the level difference between Position 9° and 90 ° is about 4,5 dB for the electric car and 2.5 dB for the diesel car. At 41.7 m, which marks the leaving of the vehicle, only the diesel car causes higher levels at the top position 90° than at the bottom position 9°. For the electric car it is the other way round. An overview of the level differences between positions 9° and 90° in relation to the driving speed and the type of vehicle is provided in Figure 7.

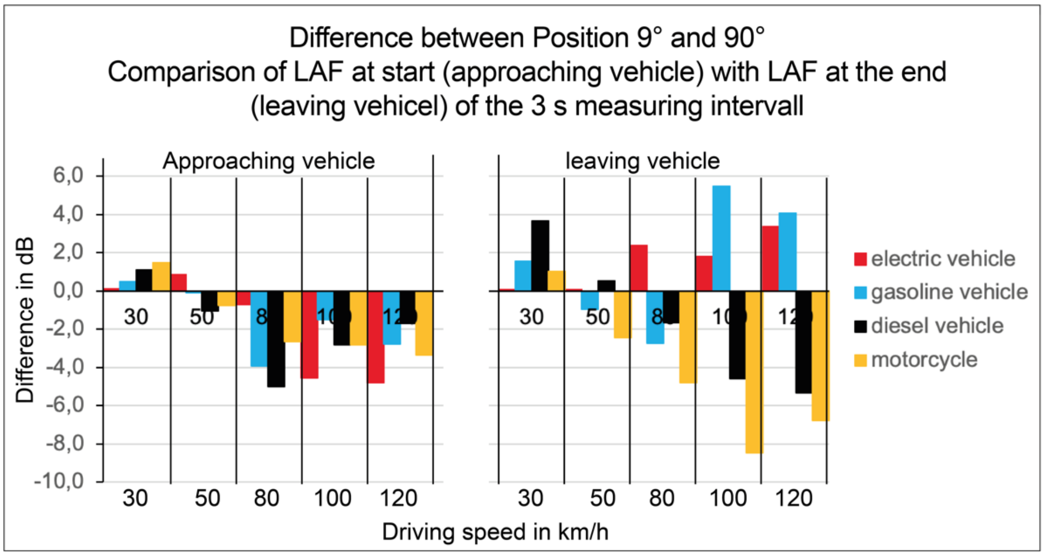

Figure 7 – Overview of the level difference between Position 9° and 90 ° in relation to driving speed and vehicle.

The overview for the approaching vehicles in Figure 7 on the left shows that for all speeds above 50 km/h the difference between positions 9° and 90° give negative results. This means a higher level reading at position 90°. For the leaving vehicles the situation is divers. The diesel car and the motorcycle show increased negative levels with higher driving speed. They emit more sound towards the vertical position 90°. In contrast, the electric car shows positive levels for all driving speeds. With increasing speed, the sound emission shifts more to the side of the electric car. The gasoline car shows no clear trend. Positive levels were determined for 30 km/h, 100 km/h and 120 km/h. The results for 50 km/h and 80 km/h show negative levels. From 100 km/h to 120 km/h the sound emission shifts from the top to the side.

3.3 Analysis of sound radiation based on LEQ calculations

Noise annoyance in urban contexts is caused by single noise events with levels high above the average noise floor or by high constant noise levels. The single noise event at maximum levels is represented by the noise level LAF. The constant noise floor is represented by LEQ values. The LEQ of levels of the 3 s measurement intervals were calculated to compare the significance between LAF and LEQ values for the directivity of sound emitted from vehicles. Figure 8 shows the increase of levels according to increased driving speed. The LAF and LEQ levels for 30 km/h were set to zero to compare the increase in levels for all vehicles. The graphs show the expected course as the calculated LEQ are always below the LAF levels. The value for the level change in relation to the driving technology is significant. Referring to Figure 4, the quietest vehicle under measurement, the electric car shows maximum levels for the noise level increase with increased driving speed. The introduction of speed limits between 30 km/h and 80 km/h to reduce traffic noise would be the most effective for electric cars.

The comparison of the difference between positions 9° and 90° calculated for LAF and LEQ levels in Figure 9 shows the same tendency. As expected, the difference for the LEQ levels is always below the one of the LAF levels. In the graphs a specific sound radiation of a vehicle is linked to a specific driving speed. In the case of the electric car the sound radiations tend more to the side positions than to the top. The motorcycle emits nearly the same sound radiation to the top as to the side. This effect becomes more apparent with increased driving speed.

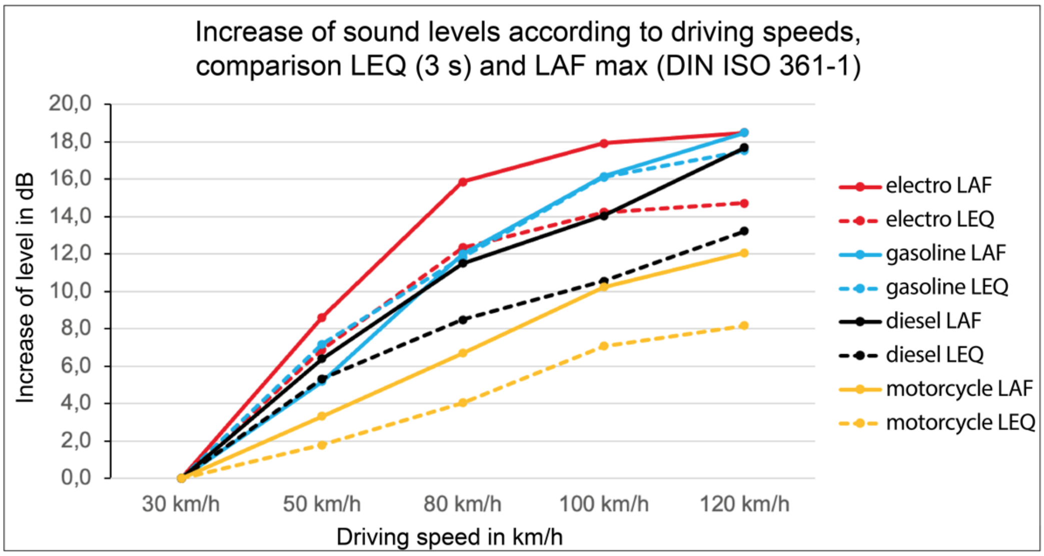

Figure 8 – Comparison of LAF and LEQ levels at Position 9°

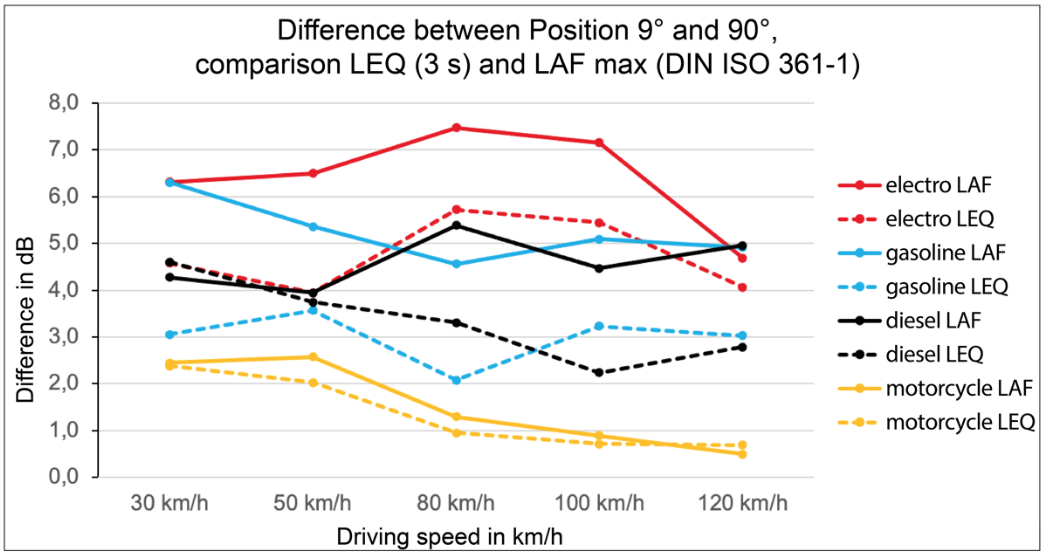

Figure 9 – Overview of the level difference between Position 9° and 90 ° in relation to driving speed and vehicle.

4 Conclusions

The results of the analyses have again validated known facts regarding the reduced noise emission of electric cars. But this measurement campaign has shown that the advantage of up to 6 dB less noise emission of electric cars emerges only at driving speeds below 100 km/h. Above 100 km/h driving speed the difference to conventional combustion engine driven cars is only around 2 dB. The comparison of the increase of emitted noise in relation to driven speed has revealed that the noise level of the electric car increases between 30 km/h and 80 km/h in steps of 6 dB or 7 dB per 10km/h. For this type of driving technology speed limits e.g., for noise reduction at night will be more effective than for conventional combustion engines. This gives the chance to adapt speed limits for the reason of noise reduction to specific environment friendly driving technologies.
Another aspect of the here presented 180° sound emission inspection of vehicles is linked to the still growing metropolitan areas. More and more road traffic runs through built-up urban areas. The road traffic noise is reflected by multiple hard reflective surfaces in urban canyons. The still growing demand of new housing spaces results in vertical solutions such as apartment high-rises. Thus, the upwards emitted sound from road traffic plays an increasingly important role for the planning of lively and healthy cities today. The further analyses of the level vs. time graph have shown that the upward emitted sound radiation is linked to the specificity of a vehicle and its driving technology. The upward emitted sound is nowadays neither covered by homologation nor considered in sound propagation. In addition, the analyses have shown that distant vehicles can radiate more noise upward than to the side. This may be one reason for the continuously growing number of complaints relating to road traffic noise.
In the framework of the ongoing research project the results of the measurement campaign will be used for further development of sound propagation methods as scaled model measurements or numerical simulations. With the determination of deviations from the normative regulated homologation of cars it becomes evident that if the regulation of the production and selling of cars is insufficient, it becomes even more important to modify the transmission paths in urban contexts wherever possible. Shifting the focus from the source to the urban fabric will lead to robust and future proof cities.

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