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SPEAKeR-Project: Simulation-based Product Development of Acoustic Systems for Electric Vehicles for the Conceptual Implementation of Adjustable Directivity

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Abstract

As road traffic becomes increasingly electrified, Acoustic Vehicle Alerting Systems (AVAS) are gaining importance. Their development involves a fundamental trade-off: vulnerable road users must be warned reliably while unnecessary sound emissions in urban environments should be minimized.

Today, AVAS are often tuned and validated only in late development phases using physical prototypes, since an accurate and computationally efficient simulation of the complete transfer path from the electrical loudspeaker input to the receiver position is not yet available. Within the SPEAKeR project, Novicos and the University of Applied Sciences and Arts Dortmund are developing a modular full-system simulation for virtual AVAS design in early vehicle-development stages.

Key methodological elements include coupled loudspeaker modeling, near-field effects, acoustic-mechanical feedback, frequency-dependent impedance surfaces, and segmented transfer paths based on reduced-order models. The simulated transfer behavior will be integrated into the sound-design process for live auralization and automated regulatory assessment.

The methodology will be validated using a Smart AVAS demonstrator with situation-dependent adjustable directivity. Unlike conventional multi-loudspeaker concepts, targeted sound guidance will be realized with a single loudspeaker system. SPEAKeR thus aims to combine improved local detectability, regulatory compliance, and reduced overall noise emissions, contributing to quieter, safer, and greater acceptance of electric mobility.

Keywords: *NVH, AVAS, automotive, sound design*

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1. Introduction

With the increasing electrification of road traffic, Acoustic Vehicle Alerting Systems (AVAS) are becoming increasingly important. At low speeds, electrically powered vehicles generate only limited propulsion noise and are therefore less readily perceived, particularly by vulnerable road users such as pedestrians, cyclists, children, and people with visual impairments. AVAS are intended to compensate for this reduced acoustic detectability and to provide early warning of an approaching vehicle. The regulatory framework is defined primarily by UN Regulation No. 138 and the US Federal Motor Vehicle Safety Standard FMVSS 141. These regulations specify requirements concerning operating conditions, frequency content, and the sound pressure levels of the generated warning signals [1]-[3].

The development of AVAS involves partly conflicting requirements for sound designers and acousticians. On the one hand, the warning signal must be clearly perceptible and reliably comply with regulatory requirements. On the other hand, the low noise emissions of electric vehicles should be preserved as an advantage of this propulsion technology. Additional sound should therefore be emitted only to the extent required for the warning function. In addition to audibility, subjective acceptance and acoustic design are relevant. The AVAS sound should clearly indicate the presence of a vehicle without being perceived as unnecessarily intrusive or annoying by pedestrians and residents [4]. At the same time, the sound is becoming increasingly important as part of a vehicle- or brand-specific acoustic identity. This results in a trade-off between effective warning performance, low environmental noise exposure, sophisticated sound design, and economically feasible development effort [5].

Addressing these conflicting objectives is further complicated by current development processes. The acoustic characteristics of an AVAS are determined not only by the generated input signal and the loudspeaker itself. The installation position and the surrounding vehicle geometry also have a substantial influence on the acoustic transfer characteristics and the resulting sound radiation. Grilles, bumpers, cavities, and air-guiding structures can cause reflections, shielding, diffraction effects, and resonances, thereby altering both the frequency response and the directivity. Consequently, an AVAS sound designed in a digital environment may be perceived substantially differently after integration into the vehicle than when the audio signal or loudspeaker is assessed in isolation [6], [7].
Reliable fine-tuning and validation currently often depend on physical vehicle prototypes. These prototypes typically become available only at a late stage of vehicle development, while short development cycles are pursued at the same time. Consequently, only a limited period remains for adapting the sound, loudspeaker position, or sound-guiding structures. At this stage, fundamental modifications are often associated with high costs or can be implemented only to a limited extent because the vehicle geometry has already been defined. AVAS development is therefore characterized by late iteration loops and a strong dependence on physical test vehicles [8].
Early simulation-based consideration of the complete acoustic transfer path could help reduce this dependence. This would require a continuous representation extending from the electrical input signal through the loudspeaker and its installation environment to the relevant receiver position. Existing approaches, however, predominantly represent individual components or partial sections of the system. A sufficiently accurate and, at the same time, computationally efficient full-system simulation remains only partially available for iterative development and sound-design processes. The SPEAKeR project addresses this gap by investigating methods for a coupled and modular simulation framework that enables vehicle-specific transfer characteristics to be considered during early development stages.

2. Numerical Modeling of the Loudspeaker System

Building on the development gap outlined above, the SPEAKeR project investigates a numerical framework for representing the complete AVAS transfer path from the electrical input signal to the sound pressure at a defined receiver position. Besides the loudspeaker itself, the surrounding vehicle geometry constitutes a major challenge for the accurate prediction of the radiated sound field.
The complete simulation chain combines electromagnetics, structural dynamics, and acoustics. Depending on the required level of detail, these physical domains can be represented by models of different complexity, ranging from analytical one-dimensional formulations to detailed three-dimensional numerical simulations. The simulation starts with the loudspeaker, where the electrical input signal is converted into membrane vibration through the interaction of the electromagnetic actuator and the structural dynamics of the transducer. A complete one-dimensional representation of this process can be achieved using the Thiele–Small equivalent circuit model [9], [10], while the acoustic radiation into the surrounding environment is represented by a 3D finite-element model. The full electrical equivalent circuit is explained in detail in [11] and shown in Fig. 1.

2.1 Fully Coupled Thiele–Small Model

For a fully coupled one-dimensional loudspeaker model, the acoustic domain fulfills two distinct functions. First, it provides the transfer function between the membrane velocity and the radiated sound pressure. Second, the acoustic impedance is required to establish the bidirectional coupling between the acoustic field and the electromechanical equivalent circuit.
By incorporating the acoustic impedance into the Thiele–Small model, the interaction between the vibrating membrane and the surrounding acoustic domain is taken into account within a fully coupled formulation. Consequently, the complete transfer function from the electrical input voltage to the radiated sound pressure can be determined while accounting for the acoustic loading acting on the loudspeaker membrane [12].

2.2 Modular Simulation Framework for AVAS Development

A continuous simulation chain covering the complete acoustic transfer path from the loudspeaker through the vehicle exterior to the pedestrian position is computationally demanding. Such a simulation must account for near-field effects, the acoustic-mechanical feedback acting on the loudspeaker membrane, as well

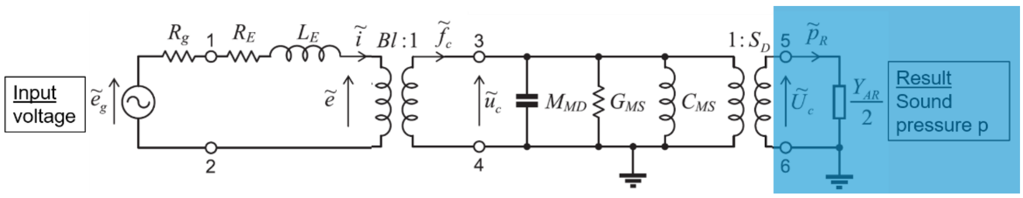

Figure 1: Sketch of coupled electrodynamic, structural and acoustical model for the transfer function from input voltage at the loudspeaker to sound pressure at a receiver position

as small geometric features, such as protective grilles, and the frequency-dependent acoustic properties of surrounding surface materials.
To support the efficient tuning of AVAS during the development process while minimizing the reliance on physical prototypes, an efficient yet sufficiently accurate numerical representation of the exterior acoustic propagation is required.
The proposed methodology aims to enable computationally efficient and real-time-capable AVAS simulations. To achieve this objective, the complete acoustic transfer path is represented by a sequence of reduced-order surrogate models. Each surrogate model describes a dedicated subsystem using computationally efficient mathematical formulations, such as analytical approximations or transfer matrices.
This modular representation significantly reduces the computational effort while allowing individual subsystems to be exchanged or refined independently. Furthermore, generic surrogate models provide an efficient basis for the comparison of different AVAS concepts during early development.

2.3 Derivation of One-Dimensional Surrogate Models

For each subsystem, a transfer matrix is derived. In the simplified representation, a subsystem is defined by two coupling interfaces, one connected to the preceding subsystem and the other to the subsequent subsystem. The acoustic state at each interface is described by the pressure p and particle velocity v. A schematic representation of the subsystem is shown in Fig. 2.
The transfer matrix is obtained by evaluating the subsystem under two independent boundary conditions. First, the interface velocities are prescribed

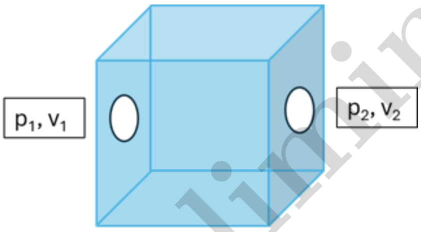

Figure 2: Sketch of a subsystem

as $v_1 = 1$ and $v_2 = 0$. In a second simulation, the complementary boundary condition is applied. The resulting interface pressures p_1 and p_2 obtained for both load cases are then used to determine the complete transfer matrix.
The proposed methodology is not restricted to purely acoustic subsystems. Depending on the application, individual modules may also represent structural components of the transfer path. Their dynamic characteristics can either be derived from numerical structural simulations or experimentally identified using blocked-force measurements [13]. As a result, the framework enables the seamless integration of simulated and experimentally characterized subsystems within a common transfer-matrix-based representation, thereby increasing both modeling flexibility and applicability during the development process.
The overall modeling approach assumes that the transfer functions of the individual subsystems can be linearly superposed. Consequently, the complete acoustic transmission path can be represented as a cascade of transfer matrices with bidirectional impedance coupling between adjacent subsystems.
A special case is formed by the final subsystem representing the acoustic radiation towards the receiver. Since no downstream subsystem exists, this element does not introduce variable acoustic feedback to the preceding subsystem.
The validity of the proposed methodology must be assessed with respect to the reduction of the coupling interfaces to one-dimensional state variables, thereby neglecting higher-dimensional variations across the interfaces. Furthermore, the formulation has to be extended and validated for an arbitrary number of coupling interfaces.
In addition, the achievable accuracy is expected to depend on frequency and on the characteristic dimensions of the coupling interfaces. Consequently, the limitations associated with increasing Helmholtz numbers must be quantified. If the Helmholtz number becomes sufficiently large, the coupling interface can be subdivided into multiple smaller segments. Although this increases the size of the resulting transfer matrices, the computational efficiency remains significantly higher than that of a fully resolved numerical simulation while extending the applicable frequency range.
The overall objective is the development of a fully coupled modular simulation framework in which all subsystem models are connected through cascaded acoustic feedback, enabling an efficient prediction of the complete AVAS transfer path.
The simulated vehicle-specific transfer characteristics will be integrated into the creative sound-design process and used for the auralization of different AVAS variants. This allows the influence of the loudspeaker, its installation environment, and the subsequent acoustic transfer path on the resulting auditory impression at a defined receiver position to be considered directly during the design of the input signal. In addition, automated evaluation algorithms will be implemented to assess the complete transfer path from the electrical input signal through the loudspeaker and the vehicle to the respective microphone position with regard to the requirements of UN R138 and FMVSS 141. This approach is intended to enable both the acoustic and regulatory tuning of an AVAS during the virtual vehicle-development phase. Consequently, dependence on physical vehicle prototypes that become available only at a late stage can be reduced, while the time available for creative sound development can be extended.

3. Smart AVAS with Adjustable Directivity

The simulation methodology described above is intended not only for predicting and auralizing the vehicle-specific transfer behavior, but also to support the targeted design of the spatial sound radiation. This is particularly relevant for operating conditions in which the receiver positions relevant to the warning function shift between the front and rear of the vehicle.

3.1 Regulatory Requirements

Acoustic Vehicle Alerting Systems are subject to different regulatory requirements in the major target markets. While type approval in UNECE contracting parties is based on UN Regulation No. 138, the Federal Motor Vehicle Safety Standard FMVSS No. 141 applies in the United States. Both regulations define requirements for the acoustic detectability of electrically powered vehicles, but differ with regard to the operating conditions considered, frequency ranges, and minimum sound pressure levels [1]-[3].

UN R138 specifies speed-dependent minimum values for the A-weighted overall sound pressure level during forward driving. In addition, minimum levels in selected one-third-octave bands and requirements concerning the speed-dependent frequency shift must be met during type-approval testing for forward driving. For reversing, a minimum A-weighted overall sound pressure level is specified.

Testing may be conducted either with the vehicle in motion or under simulated operating conditions. For indoor measurements, the vehicle may be operated on a chassis dynamometer. Alternatively, the operating condition may be simulated with the vehicle stationary by supplying external signals to the AVAS. Depending on the direction of travel, the microphones are positioned at the front or rear plane of the vehicle. The schematic arrangement of the microphone positions for a stationary measurement is shown in Fig. 3 [1].

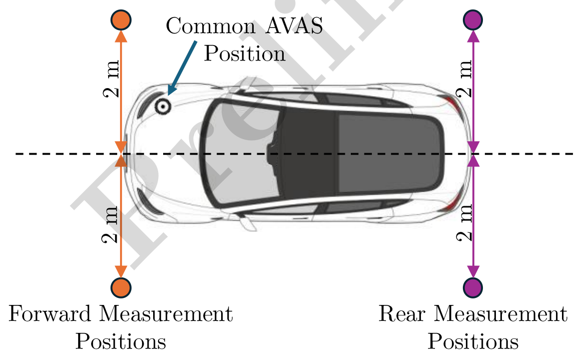

Figure 3: Conceptual illustration of the measurement positions for a stationary vehicle according to UN R138 [1]

The assessment is conducted at different reference positions depending on the direction of travel. The front plane of the vehicle is relevant for forward driving (orange markers), whereas the rear plane is relevant for reversing (violet markers).

3.2 Acoustic Challenge of a Front-Mounted Single-Loudspeaker System

An AVAS incorporating only one loudspeaker represents an economically attractive system architecture due to its low hardware complexity, installation-space demand, and integration effort. The loudspeaker is frequently installed in the front section of the vehicle. This position is generally suitable for forward driving, as the relevant measurement and receiver positions are located in front of or laterally ahead of the vehicle. The sound required to comply with the regulatory requirements can therefore be radiated towards the relevant area via a comparatively short transfer path.

The acoustic boundary conditions change during reversing. The positions relevant to regulatory assessment and the warning function are then located near the rear of the vehicle. When only a front-mounted loudspeaker is used, the sound generated by the loudspeaker must propagate along or around the vehicle towards the rear. The resulting sound pressure levels at the rear of the vehicle are influenced by factors including propagation distance, shielding effects, diffraction around the vehicle contour, and reflections from the body and underbody structures.

A substantially higher source-side sound radiation level may therefore be required to ensure the necessary sound pressure level at the rear plane. This increased radiation is not directed exclusively towards the rear of the vehicle and may simultaneously result in increased sound emissions in front of the vehicle. During reversing, this additional sound contributes only to a limited extent to the intended warning function in this area.

3.3 Exemplary Investigation of a Production AVAS

To investigate the operating-condition-dependent sound emission by way of example, a production AVAS from a Škoda Enyaq was examined. In the vehicle, the system is installed in the right-hand section of the vehicle front, as shown in Fig. 3, and is designed as a so-called one-box system. In this one-box configuration, the sound controller, audio amplifier, and loudspeaker are combined within a single housing. The system is supplied with electrical power by the vehicle and receives the required operating-condition data via the CAN bus. With this integrated architecture, the AVAS can be operated independently of the complete vehicle in a controlled acoustic environment. For the investigation, the system was positioned in an acoustic test room and supplied with the required operating voltage. A CAN rest-bus simulation was used to provide the vehicle data required for different driving speeds and directions of travel.

A microphone was positioned at a distance of 0.10 m in front of the loudspeaker opening. The two operating conditions investigated were forward driving at 6 km/h and reversing at 6 km/h. The A-weighted sound pressure level measured at this position was used as the comparison quantity. The measurement results are summarized in Table 1.

Table 1. Comparison of the sound pressure levels emitted by the AVAS at a distance of 0.10 m.

Vehicle status	Sound pressure level L_A
Forward, 6 km/h	84.5 dB(A)
Reverse, 6 km/h	96.8 dB(A)

During reverse operation, the A-weighted sound pressure level measured for the isolated AVAS was approximately 12 dB higher than during forward operation. The measurement therefore demonstrates that the two operating modes produce distinctly different source-side levels. According to UN R138.01, reverse operation at 6 km/h must achieve a minimum overall sound pressure level of 47 dB(A) at the rear-side measurement positions [1]. No corresponding minimum value is specified for forward driving at 6 km/h; the first defined forward-driving operating point is 10 km/h, for which a minimum level of 50 dB(A) is required [1]. Because both operating conditions are intended to ensure vehicle detectability in the respective direction of travel, similar detectability levels can be expected at the corresponding front and rear receiver positions. This interpretation is further supported by the later UN R138.02 requirements, which specify minimum overall sound pressure levels of the same order of magnitude for low-speed forward driving and reversing [14].

The substantially higher source-side level measured during reverse operation is therefore interpreted as compensating for the attenuation associated with sound propagation from the vehicle front to the rear-side measurement positions. Increasing the AVAS output does not exclusively raise the sound pressure level at the rear; it also increases sound emissions towards the vehicle front, where they contribute only to a limited extent to the intended warning function during reversing. Consequently, a front-mounted single-loudspeaker system may cause avoidable sound emissions in front of the vehicle when operated in reverse.

3.4 Project Approach for Adjustable Directivity

Within the SPEAKeR project, concepts are therefore being investigated that enable the directivity of a single AVAS loudspeaker to be adjusted depending on the operating condition. For this purpose, the loudspeaker system must be combined with an actuator-based adjustable sound-guiding structure. During forward driving, preferred sound radiation towards the front of the vehicle is intended. During reversing, the sound energy must be directed primarily towards the rear of the vehicle. This concept is visualized in Fig. 4.

The objective is to achieve the sound pressure levels required at the relevant positions for each operating condition without unnecessarily increasing sound emissions in irrelevant spatial directions at the same time. The approach thus combines the low hardware requirements of a single-loudspeaker system with sound radiation adapted to the operating condition and direction of travel.

The adjustable directivity therefore addresses the fundamental trade-off in AVAS development: vulnerable road users are to be warned reliably, while avoidable sound emissions for residents and road users outside the relevant warning area are to be kept as low as possible. The modular simulation methodology described above is intended to be used to compare different loudspeaker positions, sound-guiding concepts, and actuator settings already during the virtual vehicle-development phase. On this basis, suitable concepts are to be selected, investigated in greater detail, and subsequently implemented and validated experimentally in a Smart AVAS demonstrator.

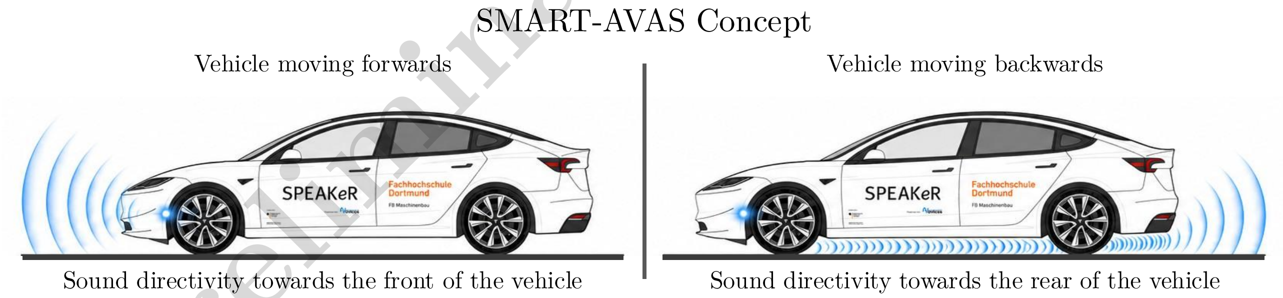

Figure 4: Conceptual illustration of a Smart AVAS with adjustable directivity

4. Conclusion and Expected Impact

The SPEAKeR project addresses two central challenges in AVAS development: the limited availability of accurate and computationally efficient full-system simulations and the need to reduce unnecessary sound emissions without compromising regulatory compliance or pedestrian safety. By combining coupled loudspeaker modeling, modular transfer-path descriptions, reduced-order surrogate models, and integration into the sound-

design workflow, the project aims to enable vehicle-specific AVAS development at significantly earlier stages of the product-development process.
The expected impact is a reduction in prototype-dependent iteration loops, shorter development times, and a more consistent integration of acoustic design and regulatory assessment. The Smart AVAS demonstrator with situation-dependent adjustable directivity will further investigate how a single loudspeaker system can direct sound toward the relevant vehicle side while reducing emissions in non-relevant directions. In this way, SPEAKeR is expected to contribute to safer, quieter, and more widely accepted electric mobility.
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