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Loudspeaker-based sound reproduction for evaluating noise transmission into the car cabin

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ABSTRACT

Virtual and laboratory-based design techniques can accelerate the development process over conventional prototype-and-field-test procedures. In car acoustics, the transmission of outside airborne noise into the cabin needs to be understood and managed. Here, we evaluate the accuracy of sound field recording and reproduction techniques for investigating the transmission of airborne noise into the driver's cabin of a car. Reference measurements of a real sound field, generated by a truck with idling engine to create a realistic scenario, were carried out in a semi-anechoic chamber. The reference sound field was recorded inside and around a test car. Additionally, a spatial recording of the reference sound field was carried out and used to reproduce the reference sound field over a loudspeaker array in a different, fully anechoic chamber, where the sound field was again measured inside and around the same test car. A comparison of the measured loudness inside the test car shows that this key parameter for sound quality could be reproduced rather faithfully over a loudspeaker array in a controlled testing facility.

1. INTRODUCTION

As car engines are becoming quieter and better isolated from the cabin of the car, the importance of a good airborne sound absorption in cars increases. Currently, the assessment of car acoustics is usually done by experienced engineers driving the car, listening and rating the acoustics for different driving scenarios. Being able to evaluate the acoustic properties of the car inside a test facility opens up possibilities to develop a series of standardized test scenarios to assess the acoustics of cars for easier comparison between car models. With reproducible spatial sound scenarios, measurement techniques for identifying air transmission paths into the cabin and even for assessing sound quality could be developed. Also, being able to showcase a car's acoustic properties without needing to drive it could allow manufacturers to showcase their acoustic design to a wider audience: from decision makers to customers.

As virtual acoustic and visual environments become more advanced, studies on the evaluation of vehicles emerged (*e.g.* [1]). More specifically for acoustics, developing objective measures for listener comfort or sound quality by trying to match listener feedback [2, 3], or placing listeners in reconstructed virtual environments emulating a vehicle to conduct listening experiments [4, 5], have shown great interest. These studies used binaurally recorded signals played back over headphones, with listeners sitting outside of the test car.

The present study investigates the potential of sound field synthesis in the free-field via loudspeakers to realistically recreate a physical sound field around and inside a car. Using a real vehicle placed in

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the virtual sound field adds realism for the listener in experiments and permits the analysis of transfer paths of airborne sound to identify and treat them, similar to the analysis of vibration transfer paths to reduce rumbling noise [6].

Two sets of measurements were carried out: a reference measurement in a semi-anechoic chamber (AGP) at the BMW testing facility in Aschheim, Germany, and an evaluation measurement in the anechoic chamber (AEC) of the Professorship of Audio-Information Processing at the Technical University of Munich. We measured the sound field created by a noisy truck inside and around a BMW 5er Series Touring (G31) test car and also took spatial recordings of the sound field in absence of the car. The spatial recordings were used to reproduce the reference sound field in a different anechoic chamber via a loudspeaker array, where the sound field was again measured at the same positions inside and around the test car.

A key contributor to sound quality and a prerequisite for listener comfort is the sound's loudness, e.g. as defined by Zwicker and standardized in ISO 532-1 [7]. Loudness has been shown to be highly correlated to acoustic comfort inside vehicles [2]. It can be computed from acoustic input in a standardized way and unlike dB(A) measures, it considers temporal fluctuations and the level-dependence of spectral information of the sound. In this paper, we compare the loudness inside the car computed from measurements in both locations.

2. MEASUREMENT AND REPRODUCTION SETUP

Thirty-three ½″ Gefell MM210 microphones (Microtech Gefell, Gefell, Germany) were placed inside and around the test car, as shown in Figure 1, in order to capture the real sound field created by a noise source. The microphones were connected to a PAK measurement system (PAK mkII, Müller-BBM VAS GmbH, Planegg, Germany) equipped with three ICM42 modules that handled the microphone power supply and data acquisition.

The microphone placement inside and around the test car was replicated in the anechoic chamber to evaluate the performance of a loudspeaker array for sound field reproduction. The reference point and origin of the coordinate system used to describe microphone positions was defined as the point between the drivers and front seat passengers ears, as indicated by the (0,0) point in Figure 1. For the following loudness analysis we concentrate on the 8 microphones inside the car, placed at the ear positions of the driver and passengers.

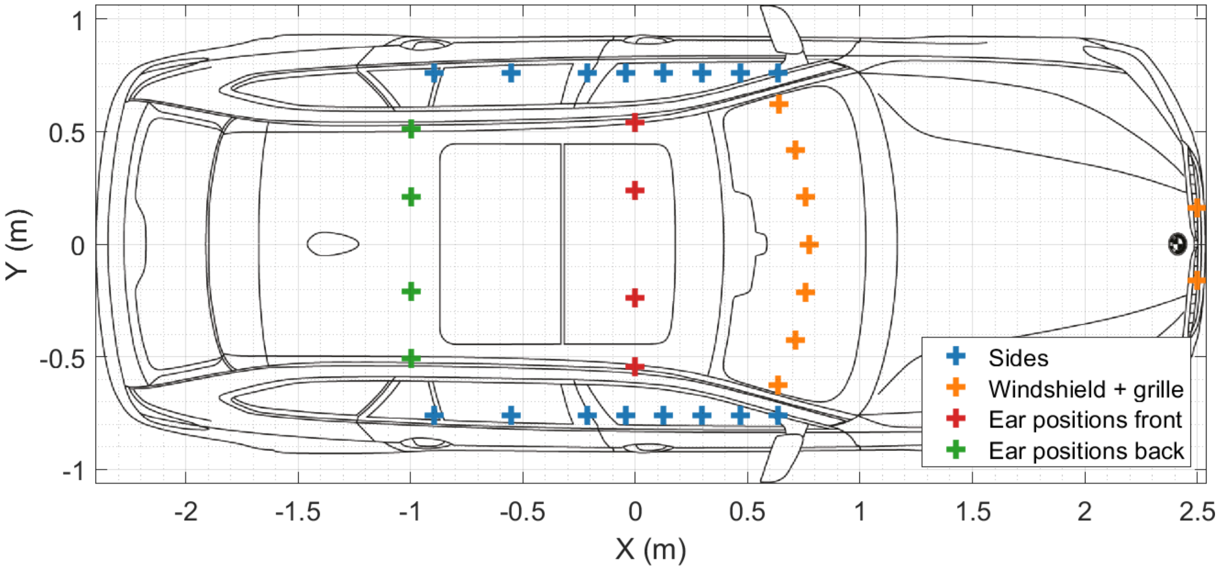


Figure 1: Microphone positions inside and around the test car.

2.1. Reference measurement at the BMW testing facility

The noise source for the reference measurement was chosen to emulate a realistic situation. A truck (Mercedes Unimog) was placed 8 m in front of the test car, its running motor served as a noise source.

The test car was then removed and the sound generated by the truck recorded with a single microphone at the reference point. A spatial recording of the sound field with a 36-channel, baffled circular microphone array [8], placed at the reference point, was also carried out.

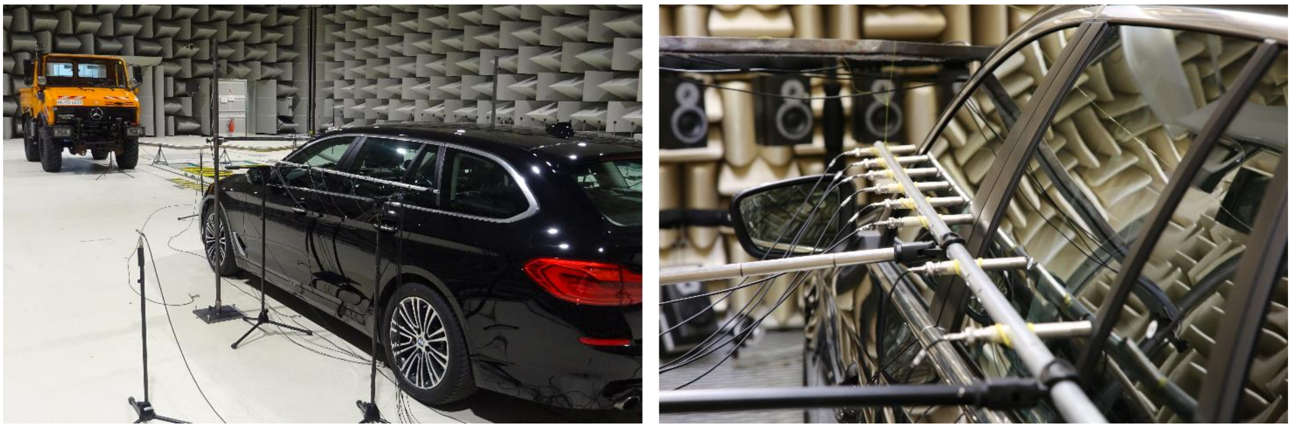


Figure 2: Reference measurement in the semi-anechoic chamber at BMW (left) and reproduced measurement in the anechoic chamber at TUM (right).

2.2. Sound field reproduction verification measurement at TUM

The measurements to assess the reproduction of the sound field were carried out in the anechoic chamber of the Professorship for Audio Information Processing of the Technical University of Munich. The test car was placed on rails inside the room. The microphone stands were placed on mounting points between the absorber wedges on the floor. The positions of the measurement microphones relative to the test car were reproduced precisely with standard placement templates and a laser distance meter.

The loudspeaker array used was part of the Simulated Open Field Environment (SOFE, v4) [9]. One side of the square loudspeaker frame had to be removed to fit the car. Out of the 27 remaining loudspeakers, only the 9 frontal ones were used (red loudspeakers in Figure 3). Since the only sound source (the truck) was located in front of the test car, this restriction should not impact the performance too much. To avoid errors due to non-ideal loudspeakers, they were equalized to ensure a flat frequency response and a linear phase at the reference point of the test car, however, their directivity will still affect the sound field across the wide reproduction area.

The spatial recording with the circular microphone array was used to extract 2D 17th-order Ambisonics signals that were then reproduced over the loudspeaker array with higher-order Ambisonics and a *basic* decoder. The extraction of Ambisonics signals from the circular microphone array recording is described in [10], the sound field reproduction method in [11].

2.3. Analyses

The analyses were computed on a 10 second snippet of the recorded microphone signals, windowed around the center. The time-varying loudness at the different microphone positions was computed using the shortened microphone signals as input for the MATLAB implementation of the method for time-varying signals standardized in ISO 532:1 [7]. The N5 loudness (loudness that is surpassed 5% of the time) was used as a comparative measure across measurement conditions.

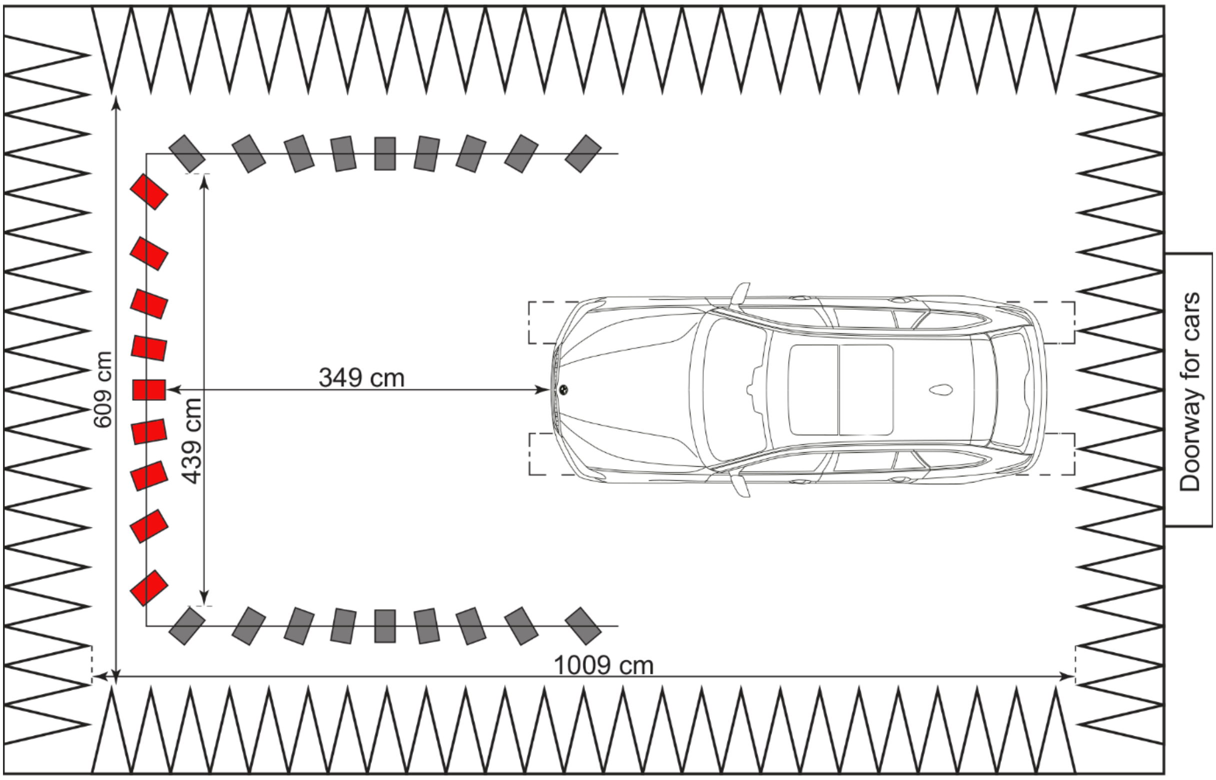


Figure 3: Sketch of the reproduction measurement in the full anechoic chamber with the car standing on a rail system. The grey and red boxes represent, respectively, the idle and the active loudspeakers during the sound field reproduction.

3. RESULTS

3.1. Measured loudness in reference condition

Figure 4 shows the measured N5 loudness inside the test car at the ear positions of driver and passengers. The mean N5 loudness inside the test car was 2.36 sone, which corresponds approximately to the loudness of pink noise at 39 dB SPL.

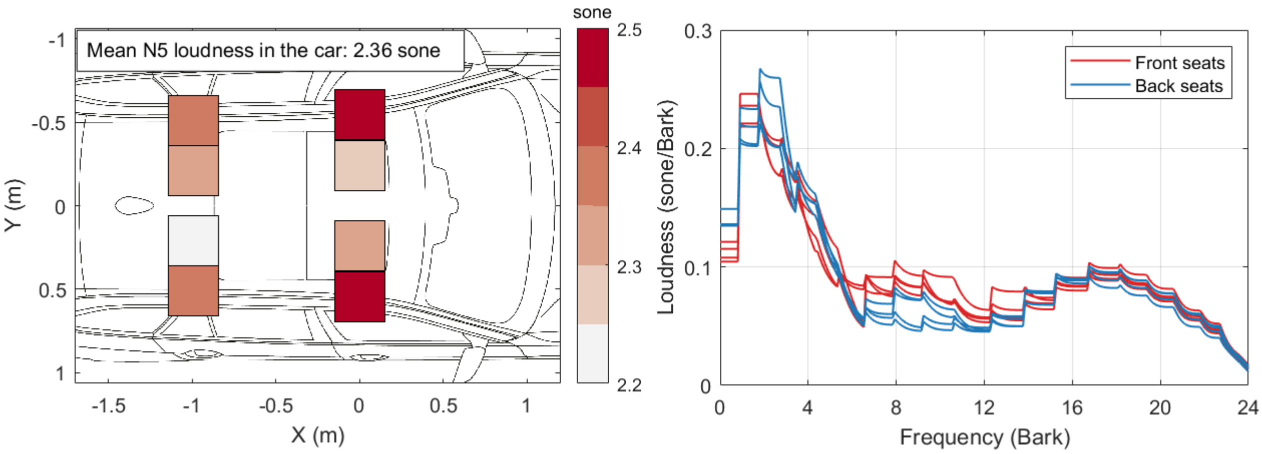
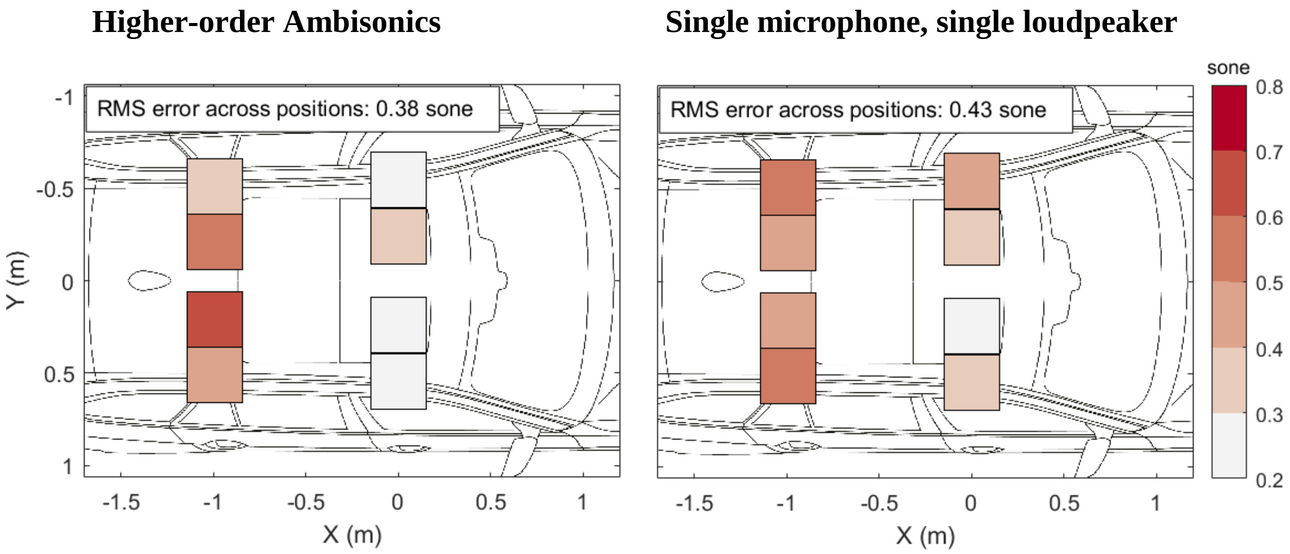


Figure 4: Left panel: N5 loudness measured inside the test car at the ear positions of driver and passengers in the real condition at the BMW testing facility. The center of the squares coincides with the measurement microphone positions inside the car, as given by the x- and y-coordinates. Right panel: corresponding specific loudness.

When looking at the specific loudness of the different microphones, we observe that by far the loudest frequency bands are the Bark bands 2 and 3, contributing 2-3-fold to loudness compared to higher frequency bands. This was expected due to the low frequency nature of the noise source, but in the extent nevertheless surprising given the elevated hearing threshold at low frequencies. Overall, we do not observe high differences in the specific loudness across microphone positions, which justifies the use of the mean value to summarize the overall loudness inside the car. However, the reference measurement shows a consistent difference between the two microphones of a given seat: the loudness is always higher for the microphone closest to the window, the difference averaging to 0.13 sone across the four seats.

3.2. Reproduction of the measured loudness


Higher-order Ambisonics

Single microphone, single loudpeaker

Figure 5: Reproduction error of the N5 loudness measured inside the test car at the ear positions of driver and passengers in the sound field reproduction condition in the anechoic chamber of TUM versus in the real condition at the BMW test facility. The RMS error across measurement positions is given for comparison.

Figure 5 shows the error between the N5 loudness in the real and in the reproduction condition. The center of the squares coincides with the measurement microphone positions inside the car, as given by the x- and y-coordinates. The N5 loudness error is relatively small, on RMS-average 0.4 sone across measurement positions for both methods compared to about 2.4 sone overall loudness. Higher-order Ambisonics (Figure 5, left panel) shows lower errors at the front seats, which is the region car manufacturers would want to optimize first. Note that the sound field recording microphone array was placed there. The absolute and relative errors are summarized in Table 1.
When looking at the four microphone pairs, it is seen that the error for the higher-order Ambisonics reproduction (Figure 5, left panel) is lower for the microphone closest to the window, meaning this method tends to reduce the difference between the loudness of two microphones of a given seat. For the single loudspeaker reproduction (Figure 5, right panel), this trend is reversed and this method increases the difference between the loudness of two microphones of a given seat.

Figure 6 indicates the difference between the specific loudness between the different conditions, which highlights the frequency dependence of the reproduction error. It is clearly visible that the frequency bands below 4 Bark drive the loudness error. This difference is especially strong for the back seats.

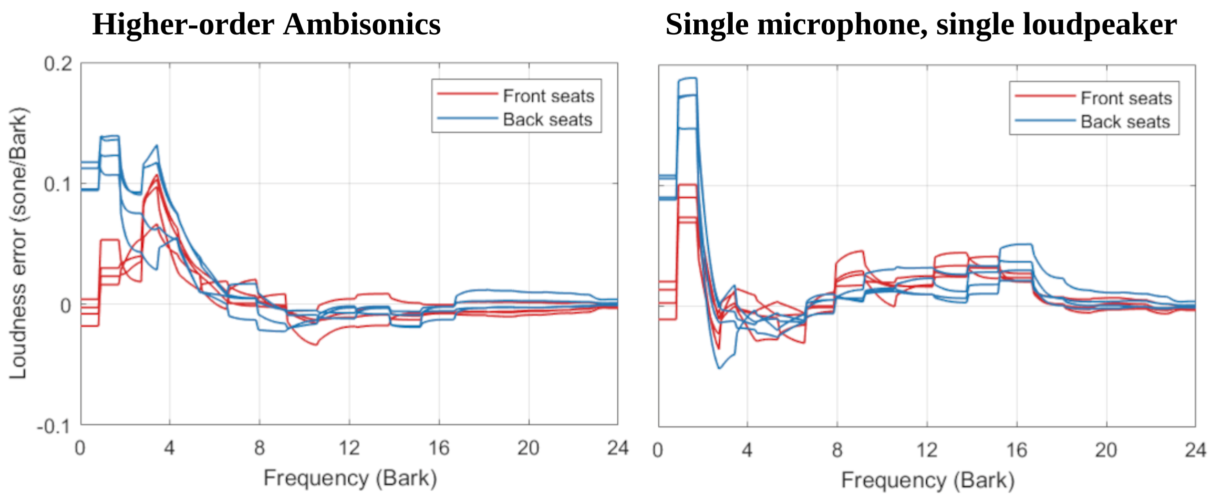


Figure 6: Specific loudness error measured inside the test car at the ear positions of driver and passengers in the sound field reproduction condition in the anechoic chamber of TUM versus in the real condition at the BMW test facility.

4. DISCUSSION

Table 1: Value of the RMS and maximum N5 loudness error inside the test car in sone and relative value in percent for the different recording scenarios.

Recording method	Rendering method	RMS error	Maximum error
Circular microphone array	17th-order Ambisonics	0.38 sone (16%)	0.62 sone (26%)
Single microphone	Single loudspeaker	0.43 sone (18%)	0.55 sone (23%)

In order to highlight the perceptual impact of the measured loudness differences, we compute the change of loudness induced by a level increase of 0.5 dB, corresponding to the just noticeable level difference (JND) for broadband noises [12]. When amplifying the recorded microphone signals by 0.5 dB, we noticed a loudness increase of 5% (0.12 sone) in the calculated loudness compared to the original recording, which can be interpreted as a loudness JND for these specific recordings. Using this definition, the RMS reproduction errors lie between 3 and 4 JNDs. We expect this difference to be noticeable. However, since A/B comparisons between the real and reproduction scenarios are difficult, this difference should not impact perceptual studies too much.

The loudness error across positions inside the car of around 0.13 sone, however, would in theory be noticeable during head movements of the listener. However, loudness changes strongly across positions due to standing waves anyway, and that “normal” change is as large or larger than the reproduction error (c.f. front vs back seats).

The low loudness errors seen for all microphones and for both reproduction methods are due to the low SNR of the measurement. For frequencies above 13 Bark (2 kHz), the SNR approaches 0 dB and the computed loudness becomes unreliable.

The higher loudness errors seen for the microphones at the back are due to the high differences in the loudness at low frequencies between the reference and reproduction conditions. One possible explanation is the build-up of standing waves inside the car cabin. For instance, a standing wave between the windshield and rear window is likely to be more noticeable at the back seats, since they are closer to the center of the car cabin than the front seats. Such a standing wave would also fall into the 100 Hz range and thus affect the loudness in the lowest frequency bands. The low-frequency error is somewhat smaller with Ambisonics reproduction, which reproduces the spatial sound field at low frequencies over a larger area more faithfully than a single loudspeaker. It might thus be that, on average, Ambisonics is better suited for characterizing airborne sound transmission through the car frame at low frequencies than a point source reproduction, and that it might excite the standing waves more faithfully.

5. CONCLUSION

We investigated the achievable reproduction accuracy with sound field synthesis techniques when reproducing measured sound fields inside and around a vehicle. Reference measurements of an idling truck in front of a BMW 5er Series Touring test car were taken in a semi-anechoic chamber. The reference sound field was measured inside and around the test car, as well as with a microphone array to capture the spatial information of the reference sound field. The recordings were then auralized with 17th-order Ambisonics and a single loudspeaker playback to reproduce the reference sound field over a loudspeaker array inside a full anechoic chamber.
An analysis of computed loudness inside the test car shows that this parameter, a key component to perceived sound quality, could be reproduced rather faithfully, with the reproduction error of the N5 loudness being around 0.4 sone across driver and passengers ear positions.
Further work may study the performance of other sound field synthesis methods such as wave-field synthesis or vector-base amplitude panning, and different sound field recording or beamforming techniques that could improve real-life recordings by removing unnecessary noise.

6. AKNOWLEDGEMENTS

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7. REFERENCES

1. Genuit, K. & Bray, W.R. A Virtual Car: Prediction of Sound and Vibration in an Interactive Simulation Environment. *SAE Transactions* **110,** 1748-1754 (2001).
2. Nor, M. J. M., Fouladi, M. H., Nahvi, H. & Ariffin, A. K. Index for vehicle acoustical comfort inside a passenger car. *Applied Acoustics*, **69(4)**, 343-353 (2008).
3. Brizon, C.J.d.S. & Bauzer Medeiros, E. Combining subjective and objective assessments to improve acoustic comfort evaluation of motor cars. *Applied Acoustics,* **73(9),** 913-920 (2012).
4. Parizet, E., Amari, M., Nosulenko, V. & Lorenzon, C. Vibro-acoustical comfort in cars at idle - human perception of simulated sounds and vibrations from three and four cylinder diesel engines. *International Journal of Vehicle Noise and Vibration,* **3,** 143-156 (2007).
5. Iachini, T., Maffei, L., Ruotolo, F., Senese, V. P., Ruggiero, G., Masullo, M. & Alekseeva, N. Multisensory Assessment of Acoustic Comfort Aboard Metros: a Virtual Reality Study. *Applied Cognitive Psychology,* **26(5)**, 757-767 (2012).
6. Shin, T., Kim, Y. S., An, K. & Lee, S. K. Transfer path analysis of rumbling noise in a passenger car based on in-situ blocked force measurement. *Applied Acoustics,* **149,** 1-14 (2019).
7. DIN ISO 532-1, *Akustik - Verfahren zur Berechnung der Lautheit* in *Teil 1: Verfahren nach E. Zwicker*, 2017.
8. Bihler, F. Design and construction of a circular microphone array for recording and reproduction of acoustic scenes. *Master's Thesis at the Professorship for Audio Information Processing, Technical University of Munich* (2017).
9. Seeber, B. U., Kerber, S. & Hafter, E. R. A system to simulate and reproduce audio-visual environments for spatial hearing research. *Hearing Research,* **260(1-2)**, 1-10 (2010).
10. Parthy, A., Epain, N., van Schaik, A. & Jin ,C. T. Comparison of the measured and theoretical performance of a broadband circular microphone array. *Journal of the Acoustical Society of America*, **130(6)**, 3827-3837 (2011).

11. Zotter, F. & Frank M. *Ambisonics: A Practical 3D Audio Theory for Recording,* Springer, 2019.
12. Fastl, H. and E. Zwicker, *Psychoacoustics, Facts and Models*. 3rd Edition, Springer, 2007.