30^th International Congress on Sound and Vibration

ICSV30 AMSTERDAM 8-11 JULY 2024

AN ENGINEERING FRAMEWORK TOWARDS A BETTER SOUND-SCAPE IN TRUCK CABINS USING METAMATERIAL ABSORBER

Zibo Liu[1,2], Xiang Fang[2], Naveen Indolia[1], Tin Oberman[2], Francesco Aletta[2], and Jian Kang[2]

[1]*Fluid Dynamics and Acoustics Simulation Group, Scania Technical Center, 151 48 Södertälje, Sweden*
[2]*Institute for Environmental Design and Engineering, The Bartlett, University College London, London WC1H 0NN*
Emails: zibo.liu, xiang.fang.22, t.oberman, f.aletta, j.kang@ucl.ac.uk, naveen.indolia@scania.com

This paper proposes a preliminary engineering approach aimed at enhancing the soundscape within truck cabins. We will map the sound pressure in the cabin to the resulting soundscape characteristics, identifying frequency bands that, while not necessarily high in sound pressure level, negatively impact the soundscape. By employing metamaterial absorbers optimized through a machine learning framework, we seek to improve the acoustic environment for truck drivers. The validity and feasibility of the proposed framework will be discussed, setting the stage for future developments in this field.
Keywords: Engineering Framework, Soundscape Enhancement, Truck Cabin Noise, Metamaterial Absorbers, Psychoacoustic Metrics.

1. Introduction

Noise has a profound impact on human health, with urban noise pollution presenting a considerable challenge. According to the EU Green Paper on Future Noise Policy, 80 million EU citizens are exposed to noise levels exceeding WHO recommendations, resulting in an economic burden estimated at 0.2-2Despite extensive regulatory efforts, such as the 2002 EU Directive on Environmental Noise, the focus on decibel reduction alone has proven insufficient. Noise annoyance is influenced by factors beyond mere acoustic energy, emphasizing the need for a comprehensive approach that integrates physical, social, and psychological dimensions. This issue is particularly pronounced for truck drivers, who are exposed to noisy environments for extended periods. Traditional noise reduction methods must be supplemented with the identification of critical frequency bands that exacerbate psychoacoustic impacts under various driving scenarios, such as cruising at certain speeds, driving on country roads, urban driving, or different times of the day.

Soundscape research, guided by the standards set out in ISO 12913, represents a shift in perspective. It values environmental sounds as resources for enhancement rather than mere disturbances to be mitigated. This approach transcends traditional physical sound measurements by incorporating psychoacoustic parameters and matrices that assess qualitative aspects of soundscapes, such as eventfulness and enjoyability. Techniques like immersive virtual reality simulations, combined with questionnaires and interviews, provide subjective insights into soundscape attributes [1]. Despite its effectiveness, this comprehensive approach reveals a gap: the absence of direct engineering tools designed to intentionally sculpt soundscapes according to ISO 12913 principles. This indicates a need for methodologies that bridge the gap between soundscape theory and practical engineered sound environments [2].

Acoustic metamaterials could potentially address this challenge, offering control over sound wave manipulation [3, 4]. Their unique band properties allow for precise targeting of specific frequencies, which is crucial for effective soundscape design [5]. Among the various types of metamaterials, those incorporating locally resonant structures, such as coiled-up space Helmholtz resonators (HR) [6] and labyrinthine designs for sound speed manipulation [7], are particularly promising. Their aesthetic appeal and extensive range of tunable parameters make them suitable for intricate soundscape engineering tasks. While theoretical foundations, simulation tools, and 3D printing technologies for creating these metamaterials are well-established, their application within soundscape engineering remains underexplored.

Given the complexity and multitude of parameters involved in designing effective metamaterials for soundscapes, machine learning (ML) is introduced as a critical tool [8]. ML facilitates the creation of an expansive database by simulating a wide array of metamaterial designs and their acoustic impacts. Furthermore, ML enables the inverse design process [9], where desired soundscape qualities inform the selection and optimization of metamaterial parameters, tailoring them to specific soundscape engineering needs.

This paper proposes a preliminary engineering approach aimed at enhancing the soundscape within truck cabins. We will map the sound pressure in the cabin to the resulting soundscape characteristics, identifying frequency bands that, while not necessarily high in sound pressure level, negatively impact the soundscape. By employing metamaterial absorbers optimized through a machine learning framework, we seek to improve the acoustic environment for truck drivers. The validity and feasibility of the proposed framework will be discussed, setting the stage for future developments in this field.

2. Preliminary Framework: From Acoustic Environment to Soundscape Perception in Truck Cabins

2.1 From Acoustic Environment to Soundscape Perception

- **Acoustic Measurements**: The process begins with precise measurements of the acoustic environment within the truck cabin, determining sound pressure distribution and levels. This data serves as a quantitative basis for subsequent psychoacoustic analysis and immersive simulations.
- **Psychoacoustic Metrics**: We transform the environmental acoustic data into psychoacoustic metrics to assess the soundscape's qualitative aspects. These metrics, including loudness, sharpness, and roughness, offer insights into the subjective human experience of sound. Utilizing the Soundscape Indices Protocol and the questionnaire from ISO/TS 12913-2:2018, we conduct soundscape surveys and analyze psychometric data. Ethical considerations are routinely addressed through risk analyses when involving human subjects, despite the low risk. Following ISO/TS 12913-3:2019 methodology, we visualize soundscape properties through eventfulness and pleasantness plots derived from our data analysis.

2.2 Immersive Virtual Reality (IVR) Integration

- **IVR Simulations**: We leverage Immersive Virtual Reality (IVR) to replicate the measured acoustic environment, creating an immersive platform for users to experience and evaluate potential soundscape alterations. This step is crucial for anticipating the perceptual outcomes of proposed changes before their physical implementation.

2.3 Acoustic Environment Enhancement via Metamaterials

- **Designing Metamaterials**: Targeting specific soundscape qualities, we employ established methods from previous studies to design metamaterials [10–12]. These include locally resonant structures for frequency attenuation and labyrinthine patterns for sound wave direction. The goal is to achieve desired acoustic outcomes tailored to enhance the soundscape.
- **Implementation**: The finely tuned metamaterials are then applied to the truck cabin's acoustic environment. The aim is to enhance the soundscape according to established psychoacoustic criteria, specifically increasing pleasantness and eventfulness as defined by ISO standards.

3. Optimization of Metamaterial Design for Enhanced Soundscapes

3.1 Mapping from Acoustic Metamaterials to Soundscape

The design of acoustic metamaterials is fundamentally guided by the goal of achieving desirable soundscape qualities. The unique properties of these materials, characterized by their effective dynamic mass density (ρ_{eff}), bulk modulus (K_{eff}), and phase velocity (c_{eff}), are engineered to manipulate sound waves in ways that contribute positively to the soundscape. By targeting specific psychoacoustic outcomes such as minimizing unwanted noise or enhancing pleasant sounds, we can directly impact perceived loudness (L) and overall soundscape quality. This mapping can be expressed as:

$$L(f, p) = f\left(\rho_{\text{eff}}(f), K_{\text{eff}}(f), c_{\text{eff}}(f)\right) \tag{1}$$

In this equation:
- $\rho_{\text{eff}}(f)$, $K_{\text{eff}}(f)$, and $c_{\text{eff}}(f)$ represent the frequency-dependent properties of the metamaterials.
- $L(f, p)$ represents the perceived loudness as a function of frequency (f) and acoustic pressure (p).

3.2 Soundscape and Machine Learning Optimization

The qualitative goals set forth by soundscape research provide the target outcomes for the machine learning optimization process. Psychoacoustic metrics, like loudness, which are integral to assessing soundscape quality, form the basis of the loss function in the optimization problem. The optimization algorithm iteratively adjusts the design parameters (x) of the acoustic metamaterials to minimize deviations from these target psychoacoustic profiles, ensuring the engineered soundscape aligns with desired perceptual attributes. This optimization process can be expressed as:

$$\min_{x} \left(L(f, p, x) + \lambda R(x)\right) \tag{2}$$

where:
- $L(f, p, x)$ represents the perceived loudness as a function of frequency (f), acoustic pressure (p), and design parameters (x).
- $R(x)$ is a regularization term that ensures the design parameters adhere to practical or physical constraints.
- λ is a weighting factor that balances the importance of the regularization term.

By minimizing this function, the optimization algorithm adjusts the design parameters to achieve the desired soundscape quality.

3.3 Feedback Loop in Metamaterial Design

The optimization process, facilitated by machine learning, directly influences the design and configuration of acoustic metamaterials. By identifying the optimal set of design parameters (x) that achieve the best possible soundscape outcomes, machine learning algorithms provide a data-driven pathway to engineer metamaterials with tailored acoustic properties. This establishes a feedback loop where the performance of metamaterials in real-world applications further refines the machine learning models, enhancing the precision of soundscape engineering efforts. This process can be summarized as:

$$\min_x (L(x) + \lambda R(x)) \rightarrow \text{Design} \rightarrow \rho_{\text{eff}}(f), K_{\text{eff}}(f), c_{\text{eff}}(f). \quad (3)$$

By integrating precise acoustic measurements, psychoacoustic analysis, immersive virtual reality, and advanced metamaterial design optimized through machine learning, this framework offers a comprehensive approach to potentially improving the soundscape within truck cabins. The interplay between the theoretical basis of acoustic physics and the practical goals of soundscape enhancement ensures that each component informs and is informed by the others, creating a cohesive strategy for soundscape management.

4. Discussion on the Validity and Feasibility of the Proposed Framework

The proposed framework for improving the soundscape in truck cabins using metamaterial absorbers optimized via machine learning is both innovative and feasible. Its validity is supported by several key factors: (**i**) Research suggests that acoustic metamaterials can precisely control and manipulate sound waves. Integrating psychoacoustic metrics ensures interventions address both physical sound levels and perceptual outcomes affecting well-being; (**ii**) Advancements in machine learning and 3D printing enable the design of complex metamaterials tailored to specific acoustic needs. Machine learning fine-tunes metamaterial properties, enhancing the precision and effectiveness of soundscape improvements; (**iii**) Using immersive virtual reality (IVR) to simulate and evaluate soundscape alterations allows practical testing before physical implementation, reducing risk and cost. Continuous feedback ensures metamaterials remain effective in real-world conditions.

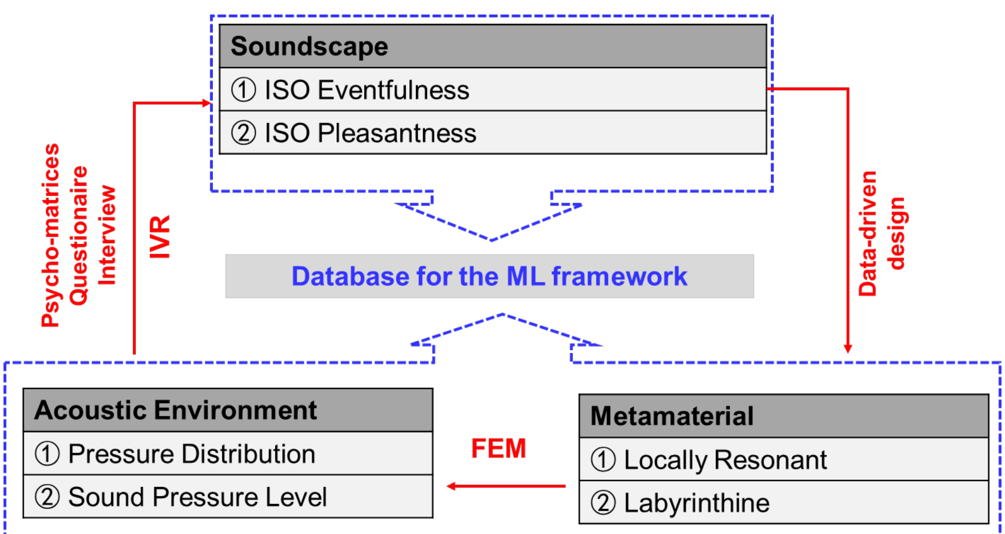

Figure 1: Conceptual Framework for Enhancing Soundscape in Truck Cabins.

The proposed framework is summarized in Figure 1, which illustrates the integration of various components and processes aimed at enhancing the soundscape in truck cabins. This scientifically sound and technologically feasible framework holds great potential for enhancing the acoustic environment in truck cabins, improving driver well-being and comfort. Future research will refine the framework and explore its broader applications, advancing soundscape engineering. A pilot study will be conducted using this framework to map the acoustic environment within a SCANIA ***R-series*** truck cabin, featuring the latest ***Super Driveline***, to specific soundscape properties.

5. Concluding Remarks

This paper outlines a preliminary framework for enhancing the soundscape in truck cabins through the use of metamaterial absorbers and machine learning optimization. Further research and validation are necessary to confirm the framework's effectiveness. The exploratory nature of this approach opens avenues for future advancements in soundscape engineering using the metamaterial concept, potentially improving acoustic environments for truck drivers and other applications.

6. Acknowledgments

Scania Department of Aftertreatment Systems and Scania Research Office are acknowledged for the financial support of this ongoing project.

REFERENCES

1. Xu, C., Oberman, T., Aletta, F., Tong, H. and Kang, J. Ecological validity of immersive virtual reality (ivr) techniques for the perception of urban sound environments, *Acoustics*, **3** (1), 11–24, (2020).

2. Aletta, F., Xiao, J. and Kang, J. Identifying barriers to engage with soundscape standards: Insights from national standards bodies and experts, *JASA Express Letters*, **4** (4), (2024).

3. Fusaro, G., Yu, X., Cui, F. and Kang, J. Development of a metamaterial for acoustic and architectonical improvement of window design, *Proceedings of the 23rd International Congress on Acoustics*, vol. 2019, pp. 1977–1983, RWTH Publications, (2019).

4. Fusaro, G., Kang, J. and Chang, W. Effective soundscape characterisation of an acoustic metamaterial based window: A comparison between laboratory and online methods, *Applied Acoustics*, **193**, 108754, (2022).

5. Cummer, S., Christensen, J. and Alù, A. Controlling sound with acoustic metamaterials, *Nature Reviews Materials*, **1** (3), 1–13, (2016).

6. Magnani, A., Marescotti, C. and Pompoli, F. Acoustic absorption modeling of single and multiple coiled-up resonators, *Applied Acoustics*, **186**, 108504, (2022).

7. Zhang, C. and Hu, X. Three-dimensional single-port labyrinthine acoustic metamaterial: Perfect absorption with large bandwidth and tunability, *Physical Review Applied*, **6** (6), 064025, (2016).

8. Nieto-Mora, D., Rodríguez-Buritica, S., Rodríguez-Marín, P., Martínez-Vargaz, J. and Isaza-Narváez, C. Systematic review of machine learning methods applied to ecoacoustics and soundscape monitoring, *Heliyon*, (2023).

9. Bastek, J., Kumar, S., Telgen, B., Glaesener, R. and Kochmann, D. Inverting the structure–property map of truss metamaterials by deep learning, *Proceedings of the National Academy of Sciences*, **119** (1), e2111505119, (2022).

10. Liu, Z., Rumpler, R. and Feng, L. Broadband locally resonant metamaterial sandwich plate for improved noise insulation in the coincidence region, *Composite structures*, **200**, 165–172, (2018).

11. Liu, Z., Rumpler, R. and Feng, L. Locally resonant metamaterial curved double wall to improve sound insulation at the ring frequency and mass-spring-mass resonance, *Mechanical Systems and Signal Processing*, **149**, 107179, (2021).

12. Song, Y., Feng, L., Liu, Z., Wen, J. and Yu, D. Suppression of the vibration and sound radiation of a sandwich plate via periodic design, *International Journal of Mechanical Sciences*, **150**, 744–754, (2019).