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Towards numerical models for seismic and Newtonian noise due to anthropogenic sources

Source identification

Anthropogenic vibration sources (figures 1 and 2) in the Euregio Meuse-Rhine (EMR):

- Roads and railway lines (Montzen route L24, HSL3)
- Wind turbines (Aachen wind farm)
- Quarries
- Industry

Figure 1: Examples of vibration sources: railway traffic, wind turbines and mining activity.

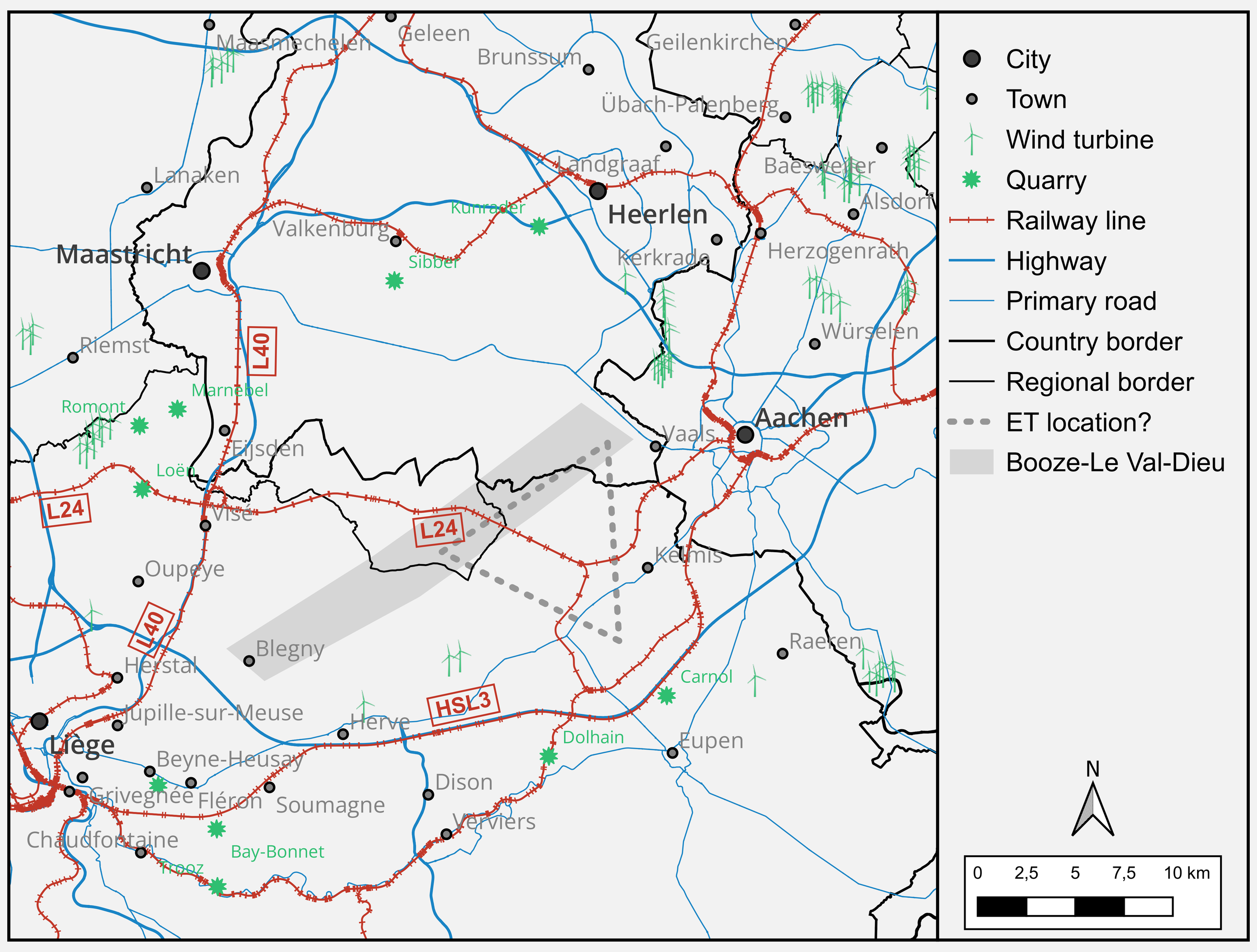

Figure 2: Location of vibration sources in the EMR.

Source characterization (railway traffic)

Imperfect wheels moving along an uneven track (alignment, rail joints, landscape variations...) generate **dynamic axle loads**. Wheel and track **unevenness** is described by a PSD (figure 3a), while the PSD of dynamic axle loads (figure 3b) is characterized by:

- Vehicle suspension modes (S_1 and S_2, 1-10 Hz)
- Resonance of the coupled axle-track system (P_2, 50-90 Hz)

Between 1 and 10 Hz, the dynamic axle loads are highest for the freight train (no secondary suspension); at higher frequencies, the axle loads for the Thalys train are highest (higher speed results in higher unevenness). The P2 resonance frequency decreases with increasing axle mass.

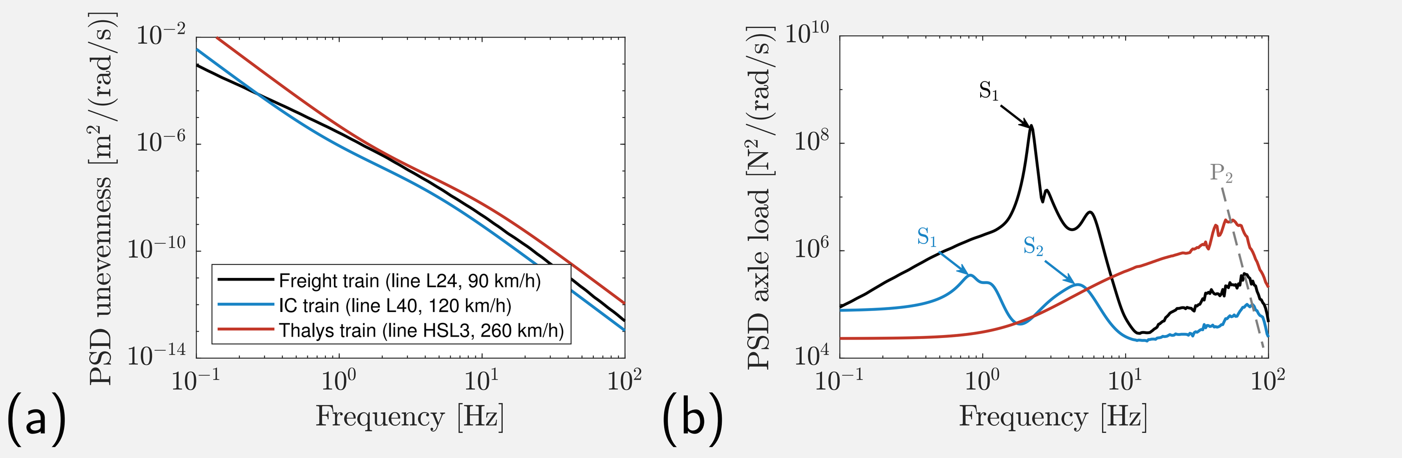

Figure 3: PSD of (a) track unevenness and (b) dynamic axle loads for freight, IC and Thalys trains.

Seismic noise (railway traffic)

Seismic noise is predicted by:

1. **Transfer functions** for horizontally layered soil (**Terziet** profile from [Bader et al. (2022)]) computed with the ElastoDynamics Toolbox [Schevenels et al. (2009)].
2. Multiplying the transfer functions with the **dynamic axle loads**.

Figure 4 shows the predicted PSD of the acceleration compared to measurements in the Terziet borehole [Koley et al. (2022)]. The freight train generates the highest acceleration around 2-3 Hz. The freight line L24 is situated at about 3 km from the borehole.

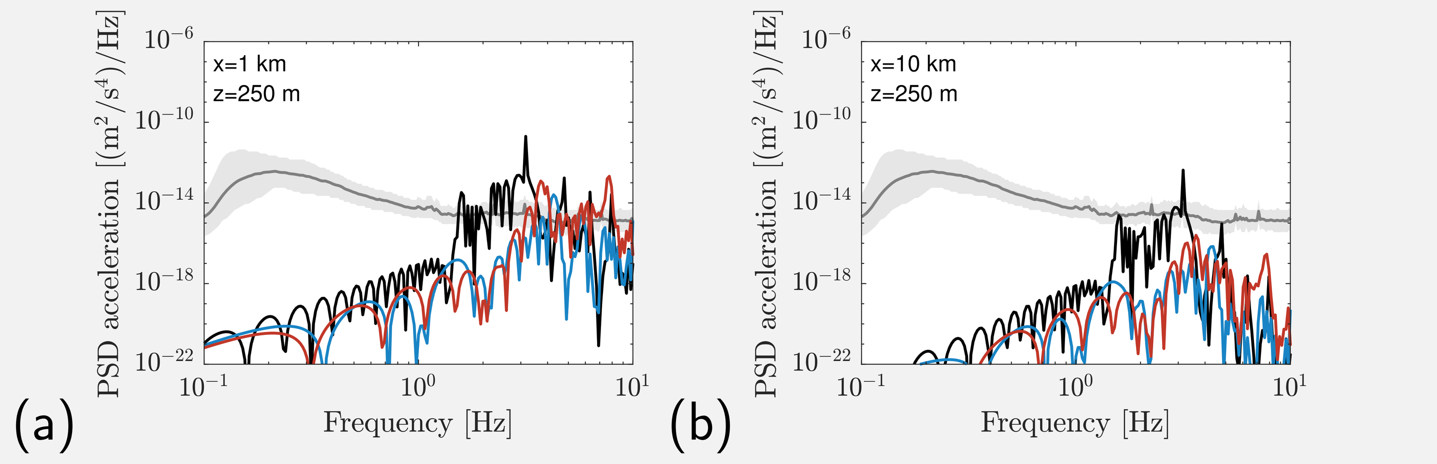

Figure 4: PSD of ground acceleration at (a) 1 km and (b) 10 km from the track. Measured borehole data (gray) are compared to numerical predictions for freight, IC and Thalys trains.

Newtonian noise (NN) model

Contributions to NN $\delta\hat{\mathbf{a}}(\mathbf{x}_0,\omega)$ at test mass location $\mathbf{x}_0$ due to seismic displacements $\hat{\mathbf{u}}(\mathbf{x},\omega)$ and density fluctuations $\delta\hat{\rho}(\mathbf{x},\omega)$:

1. Bulk contribution:

$$\delta\hat{\mathbf{a}}_{\mathrm{b}}(\mathbf{x}_0,\omega) = G\int_V \delta\hat{\rho}(\mathbf{x},\omega)\frac{\mathbf{x}-\mathbf{x}_0}{|\mathbf{x}-\mathbf{x}_0|^3}\mathrm{d}V \quad (1)$$

2. Surface contribution:

$$\delta\hat{\mathbf{a}}_{\mathrm{s}}(\mathbf{x}_0,\omega) = G\int_S \rho(\hat{\mathbf{u}}(\mathbf{x},\omega)\cdot\mathbf{n})\frac{\mathbf{x}-\mathbf{x}_0}{|\mathbf{x}-\mathbf{x}_0|^3}\mathrm{d}S \quad (2)$$

The soil domain with cavity is discretized with finite elements (FE). Using **Gaussian quadrature**, the NN contributions are computed as:

$$\delta\hat{\underline{\mathbf{a}}}_{\mathrm{b}} = \mathbf{A}_{\mathrm{b}}\hat{\underline{\mathbf{u}}} \quad \text{and} \quad \delta\hat{\underline{\mathbf{a}}}_{\mathrm{s}} = \mathbf{A}_{\mathrm{s}}\hat{\underline{\mathbf{u}}} \quad (3)$$

where $\mathbf{A}_{\mathrm{b}}$ and $\mathbf{A}_{\mathrm{s}}$ are $3\times n_{\mathrm{DOF}}$ matrices, independent of $\hat{\mathbf{u}}(\mathbf{x},\omega)$.

Figure 5 shows the **validation** of the NN model for a plane P-wave in a fullspace with spherical cavity ($r_0 = 20$ m). The domain size R is gradually increased with respect to the wavelength $\lambda_{\mathrm{p}} = 80$ m.

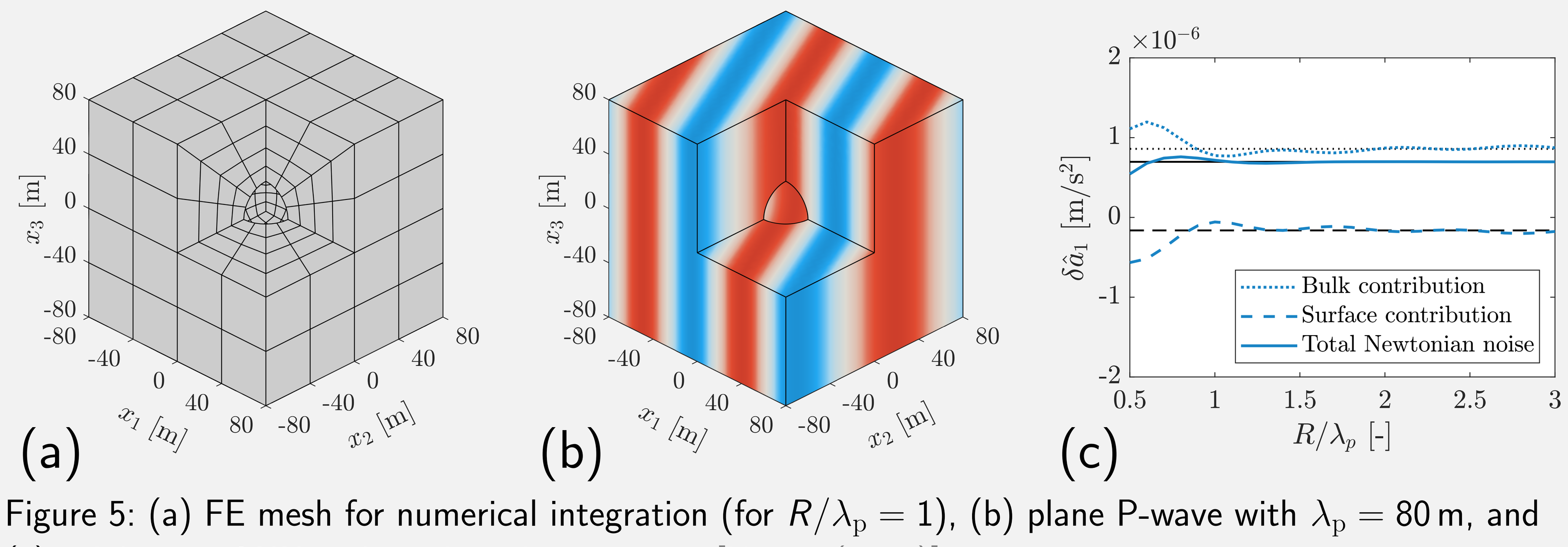

Figure 5: (a) FE mesh for numerical integration (for $R/\lambda_{\mathrm{p}} = 1$), (b) plane P-wave with $\lambda_{\mathrm{p}} = 80$ m, and (c) validation of NN with analytical expressions [Harms (2019)].

Wave scattering? Subdomain formulation [Papadopoulos et al. (2018)]:

1. Incoming wave field $\hat{\mathbf{u}}_{\mathrm{inc}}$ (without cavity), locally diffracted wave field $\hat{\mathbf{u}}_{\mathrm{d0}}$ and scattered wavefield $\hat{\mathbf{u}}_{\mathrm{sc}}$ (FE-PML model).
2. Wave field in soil: $\hat{\mathbf{u}} = \hat{\mathbf{u}}_{\mathrm{inc}} + \hat{\mathbf{u}}_{\mathrm{d0}} + \hat{\mathbf{u}}_{\mathrm{sc}}$.

Outlook

1. A detailed geological model is required to improve predictions.
2. Source models for wind turbines will be developed next.
3. Vibration map of the EMR:
   - Identify suitable locations for ET corner positions
   - Assess vibration mitigation measures (e.g. TMDs for wind turbines)

Acknowledgements

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