Politecnico di Milano
M.Sc. in Mechanical Engineering

VEHICLE ACOUSTICS

Lab. 03: Pass-by noise of rail vehicles

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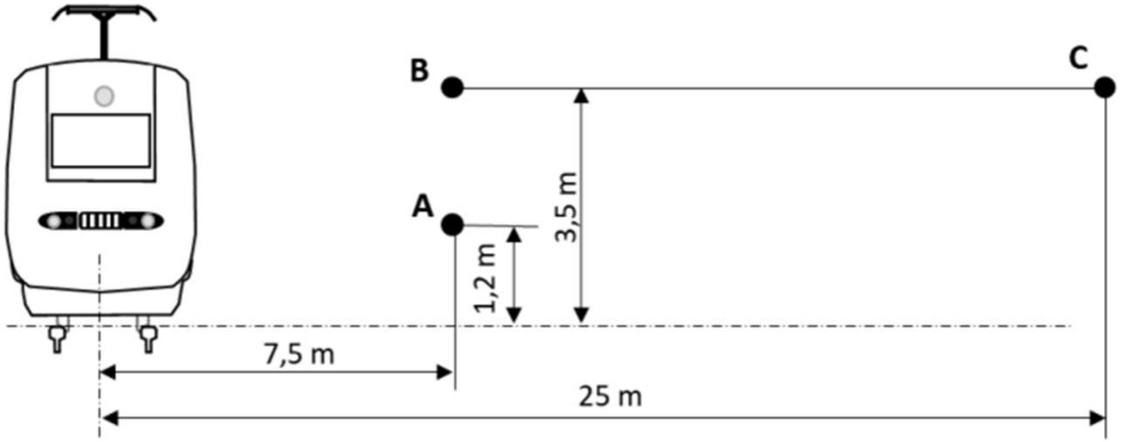
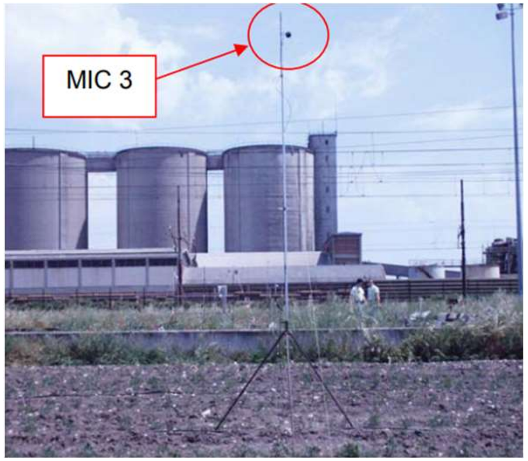
Exterior noise – pass-by tests

The measurement procedure for **exterior noise of railway vehicles** is regulated by the EN 3095 standard, which outlines a dedicated process for vehicle noise assessment during **pass-by tests**. Microphones are positioned to allow free sound propagation within a triangular area defined by the track, the microphone, and the longitudinal distance along the track. Measurement positions are specified as follows:

- for standard tests, the microphone should be positioned 7.5 meters from the track centerline at a height of 1.2 meters above the rail's upper surface.
- for speeds equal to or greater than 200 km/h, the measurement position can alternatively be located 25 meters from the track centerline at a height of 3.5 meters above the rail's upper surface.

Measurements include the A-weighted equivalent continuous sound pressure level $L_{pAeq,Tp}$ and the pass-by time T_p.





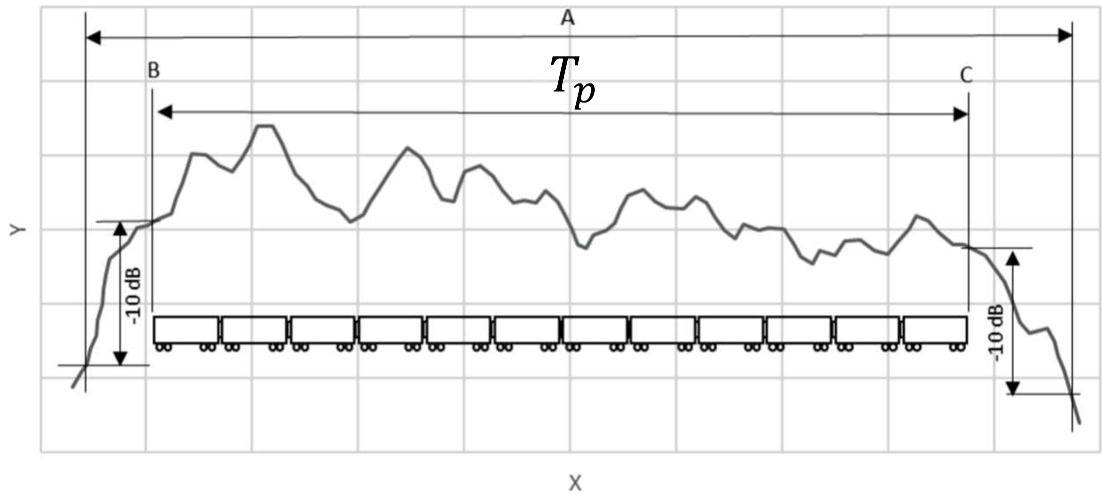
(Left) Panoramic representation of the microphone placements, from EN 3095 standard. (Right) Microphone placed according to position B of EN 3095 standard during pass-by tests, from [10].

Exterior noise – pass-by tests

The recording time interval A should be chosen so that the recording begins when the A-weighted sound pressure level $L_{pAeq,T}$ is at least 10 dB lower than the level observed when the front of the train aligns with the microphone position. The recording should continue until the A-weighted sound pressure level is 10 dB lower than the level recorded when the rear of the train aligns with the microphone.

The A-weighted equivalent continuous sound pressure level $L_{pAeq,Tp}$ is then calculated as follows:

$$L_{pAeq,T_p} = 10\log_{10}\left(\frac{1}{T_p}\int_0^{T_p}\frac{p_A^2(t)}{p_0^2}\,dt\right)$$



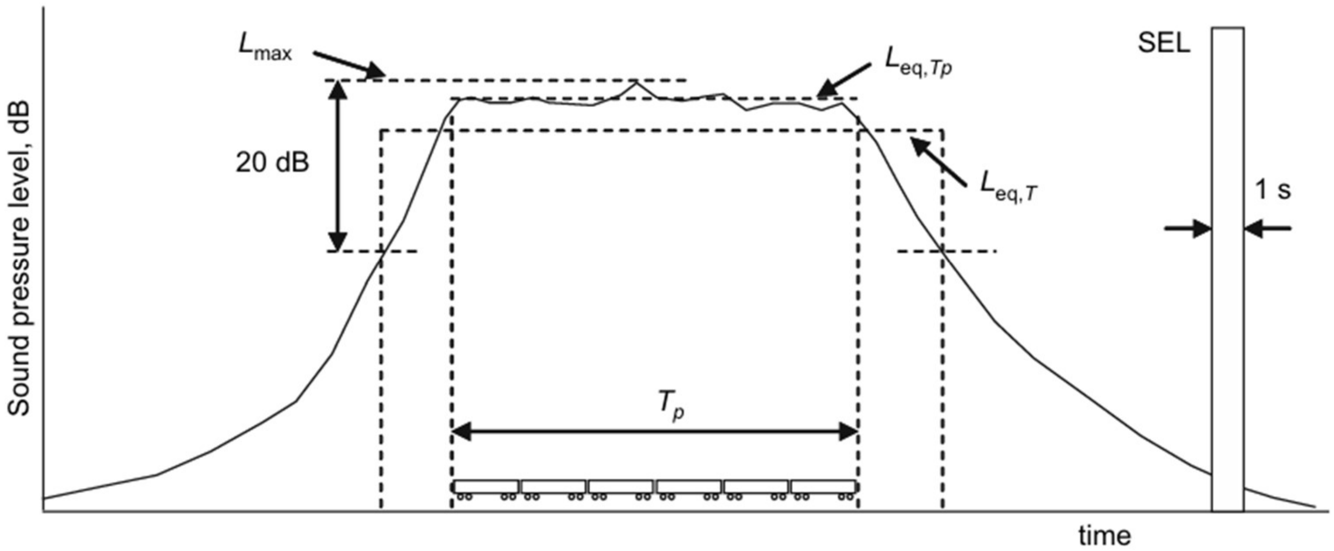
Representation of recording time interval A and pass-by time T_p , adapted from EN3095 standard.

Exterior noise – pass-by tests

Another important performance index is the Total Emission Level (TEL). This index is calculated by considering the a-weighted pressure integrated over a reference time window delimited by t_1 and t_2, defined as the time instants in which the SPL drops 20 dB below the maximum value L_{Max}. T_p indicates a time window obtained as the ratio between vehicle length and average vehicle speed during the acquisition.

The TET is then calculated as follows:

$$\mathrm{TEL} = 10\log_{10}\left(\frac{1}{T_p}\int_{t_1}^{t_2}\frac{p_A^2(t)}{p_0^2}\,dt\right)$$



Typical time history of train pass-by noise indicating various quantities, from [1].

Exterior noise – sound source mapping (beamforming)

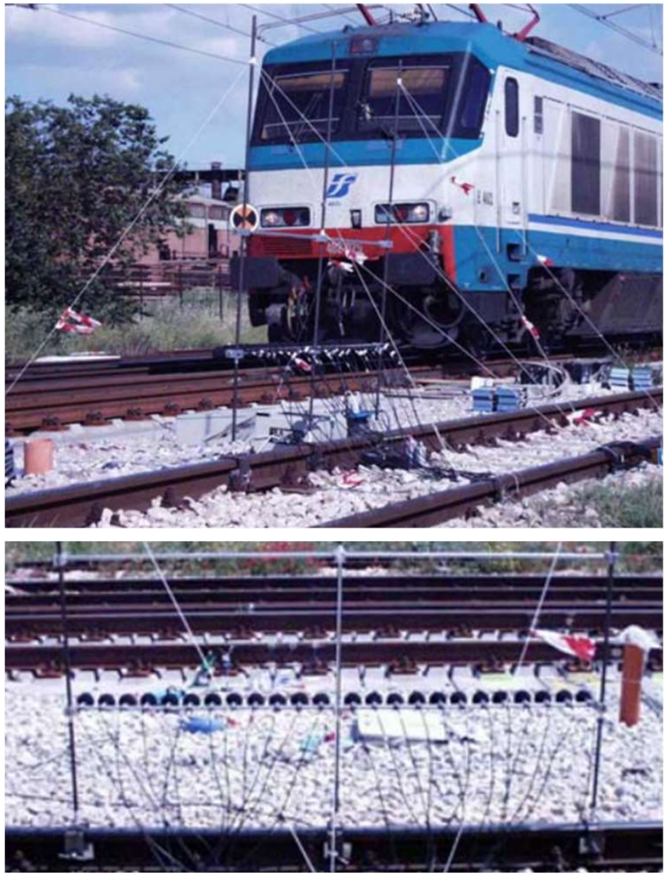
Measurements of noise contributions could not be conducted directly in the source region, e.g. aerodynamic noise due to the presence of turbulent airflow. Microphones placed within this region would pick up turbulent fluctuations, capturing contributions unrelated to sound radiation in the far field. Additionally, placing a microphone within the turbulent flow would disrupt the flow itself and create a dipole source, unless windshields are used.

For these reasons, **microphone arrays** are commonly used for measuring pass-by noise.

These arrays consist of multiple microphones arranged in specific patterns, such as linear, two-dimensional (+, x, or star-shaped) configurations.

By combining signals from multiple sensors, microphone arrays use techniques like the 'beamforming' algorithm to isolate sound originating from a specific direction.

Microphone arrays are suitable for measuring and separating the contribution of rolling noise, aerodynamic noise, pantograph,…



Single directional microphone array (24 microphones) implemented for pass-by measurements, from [10].

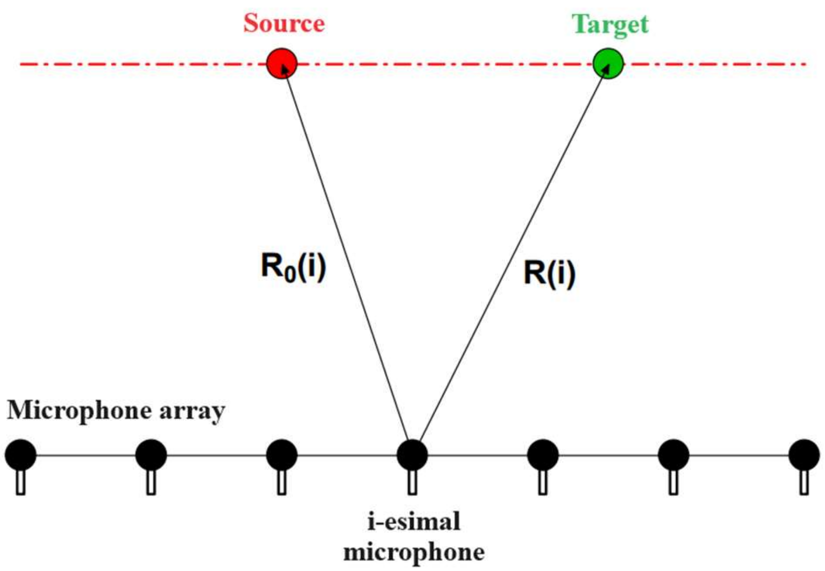
Exterior noise – sound source mapping (beamforming)

Under the hypotheses:

- spherical emission of the source
- harmonic source

consider a **linear microphone array** with evenly spaced microphones observing a fixed source. The spherical source generates a harmonic pressure S_s at time t_s:

$$S_s(t) = S_0 e^{j\omega t}$$



If we define $R_0(i)$ as the distance from the source to the i-th microphone and $R(i)$ as the distance from a target location to the i-th microphone, the i-th microphone will receive the signal at time $t_r(i)$.

$$t_r(i) = t_s + \frac{R_0(i)}{c}$$

The signal received at microphone i, denoted S_r, will exhibit a decreased amplitude, which can be approximated linearly.

$$S_r(t,i) = \frac{S_s\left(t - \frac{R_0(i)}{c}\right)}{R_0(i)}$$

By analyzing S_r and t_r, it is possible to reconstruct the original signal S_s, taking into account the distance $R(i)$ between the i-th microphone and the hypothetical source.

$$S_s(t_s, i) = S_r\left(t + \frac{R(i)}{c}\right) R(i)$$

Exterior noise – sound source mapping (beamforming)

The algorithm estimates S_s for all N microphones and averages the results. This approach, known as '**delay-and-sum**', applies a delay to each signal to account for the relative phase differences among them. If the target location matches the actual source, the averaging process amplifies the output because the signals are in phase. Conversely, if the target location does not match the source, the averaging process attenuates the output due to the phase differences among the signals.

Initially, the output can be represented in the time domain as a function of a specific location:

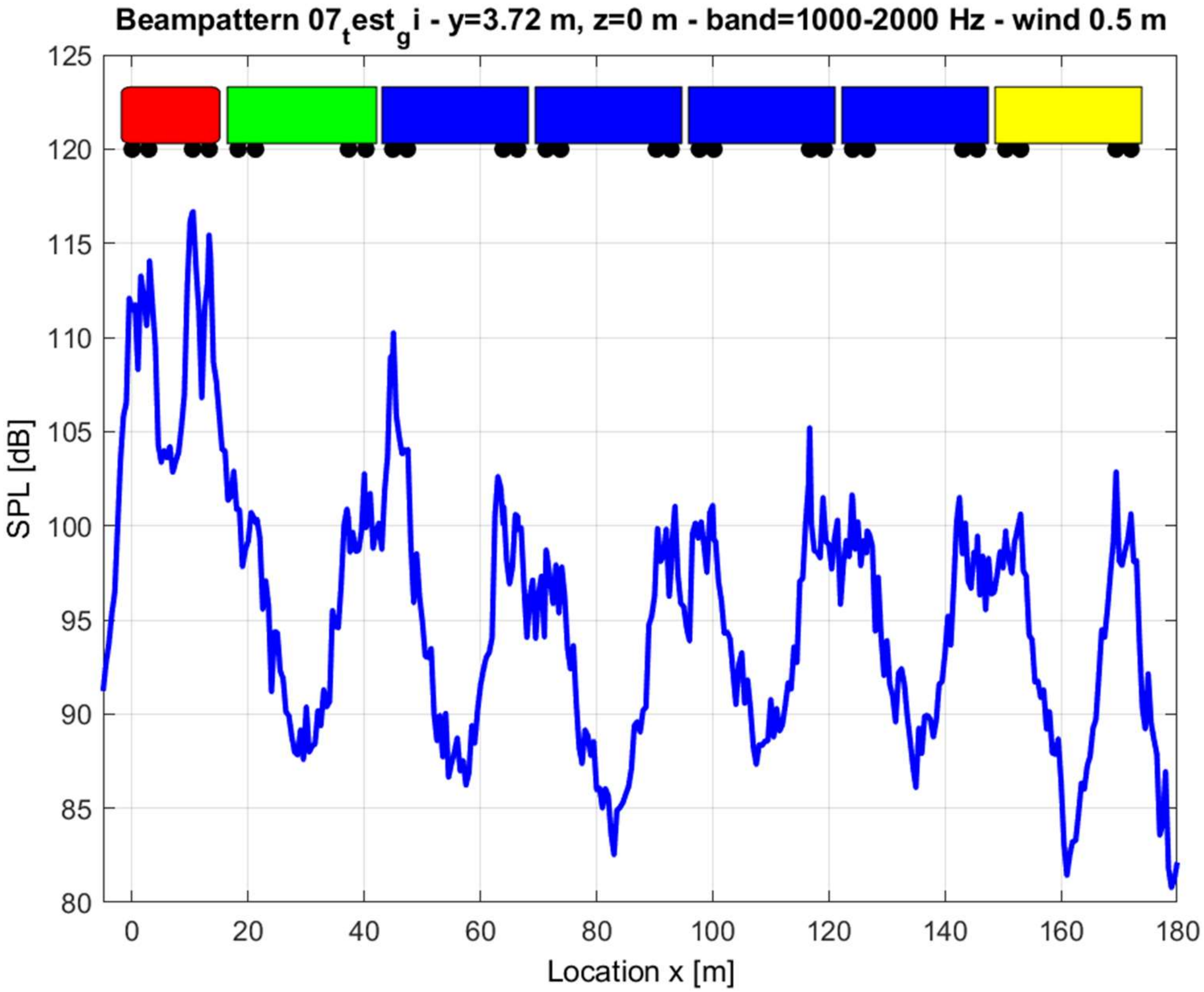
$$S_D(t, loc) = \frac{1}{N}\sum_{i=1}^{N} R(i) S_r\left(t + \frac{R(i)}{c}\right) = \frac{1}{N}\sum_{i=1}^{N} \frac{R(i)}{R_0(i)} S_s\left(t - \frac{1}{c}\left(R_0(i) - R(i)\right)\right)$$

The result can be obtained in the frequency domain by extracting the time-independent terms from the integral and considering the wavenumber k=ω/c:

$$S_D(\omega, loc) = S_0\left[\frac{1}{N}\sum_{i=1}^{N} \frac{R(i)}{R_0(i)} e^{-jk\left(R_0(i) - R(i)\right)}\right]$$

Exterior noise – sound source mapping (beamforming)

A typical result from beamforming algorithm applied to microphone arrays for the measurement of rail pass-by:



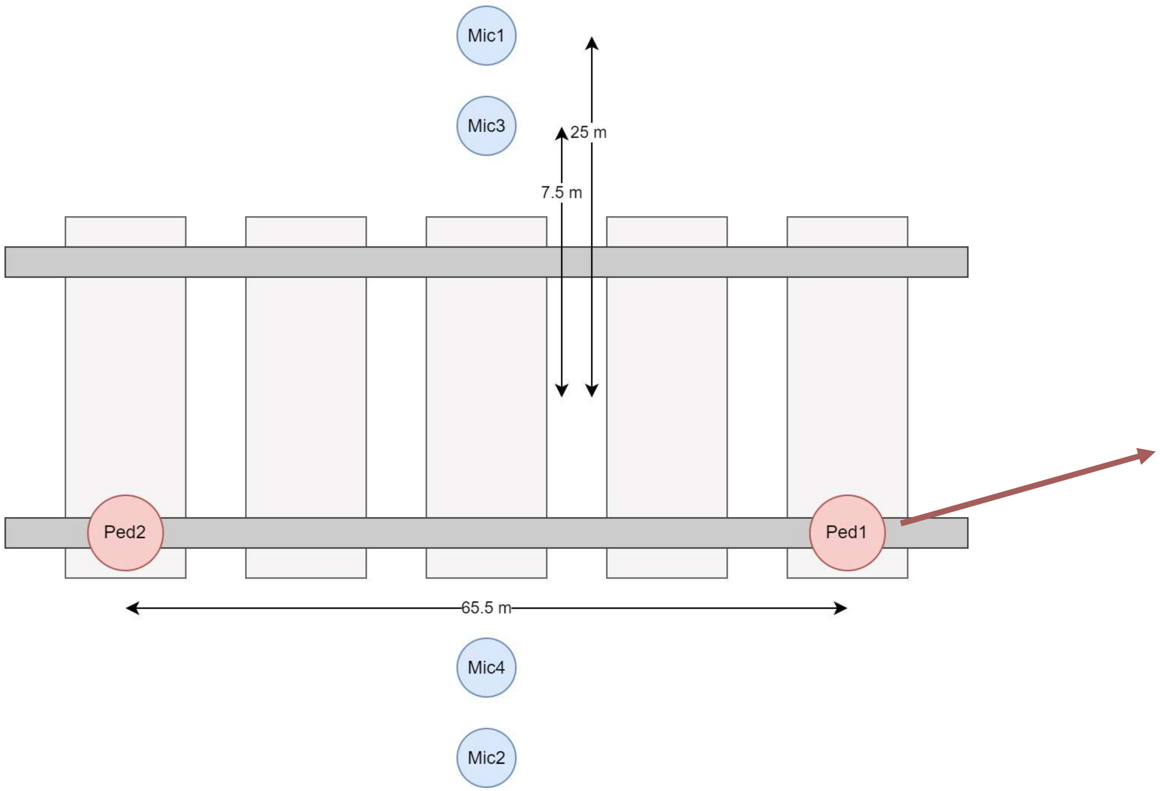
Experimental layout

In this laboratory assessment, pass-by measurements acquired during an experimental campaign are provided to perform pass-by post process.

The experimental measurements were obtained by considering a test-vehicle composed of a E402A locomotive, one instrumented wagon, 4 “gran comfort” wagons and a further single wagon. The train length is equal to 174 m.

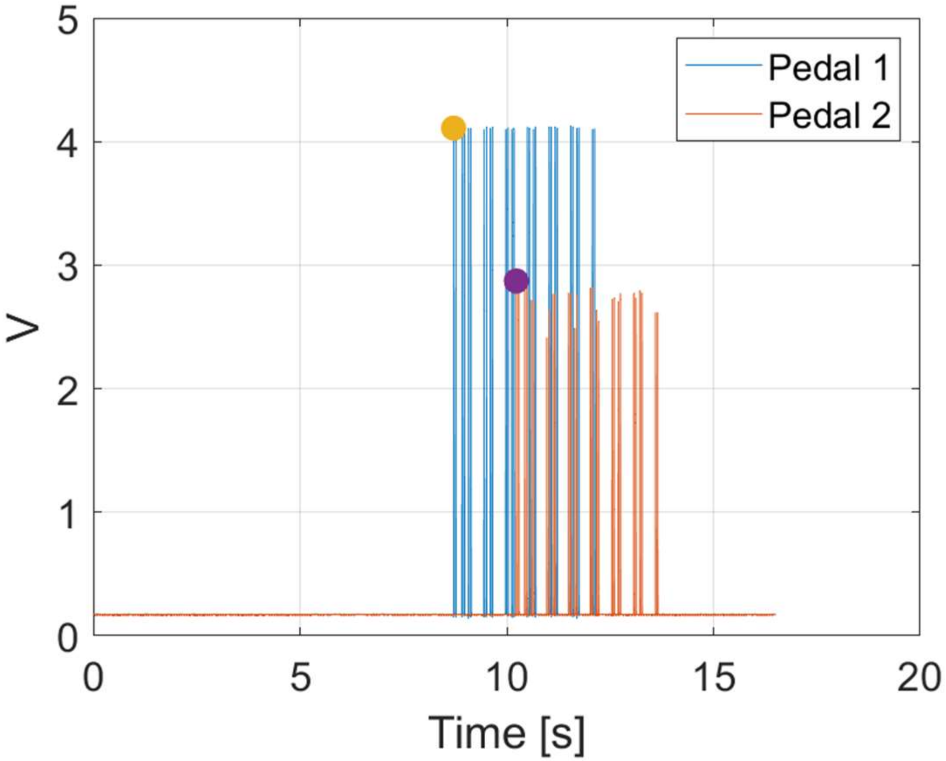
Experimental layout

Experimental measurements are performed with 4 microphones placed according to EN 3095 standard (Mic1, Mic2, Mic3 and Mic4). Moreover, two pressure sensors (Ped1, Ped2) are placed at 65.5 m of distance to measure the passing over of rail wheelsets. The signals are acquired with a sampling frequency of 16384 Hz. Seven pass-by acquisitions are recorded. **Microphone signals are provided in Pa.**



Experimental layout

Focusing on a single pass-by test, the Ped1 & Ped2 signals allow to quantify the vehicle speed. Indeed, knowing the train length, the time period between the first peak of Ped1 and Ped2 allows to obtain the average vehicle speed. Vehicle speed can also be used to calculate T_p. The time domain signal of the four microphones is also available. The microphone signals are already expressed in Pa.

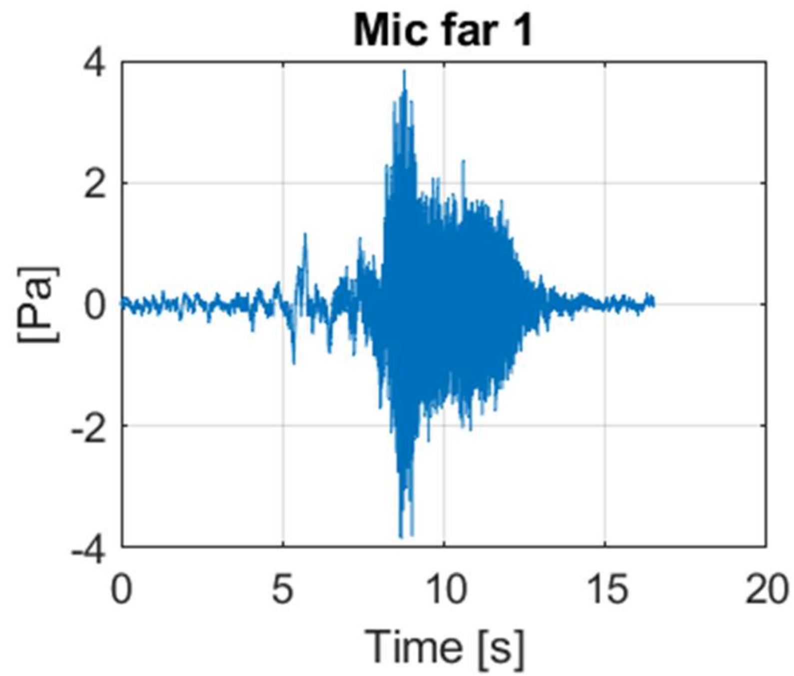


$$\text{TEL} = 10\log_{10}\left(\frac{1}{T_p}\int_{t_1}^{t_2}\frac{p_A^2(t)}{p_0^2}dt\right)$$

First, the pressure signals of the microphone must be filtered according to the A-weighting frequency filter.

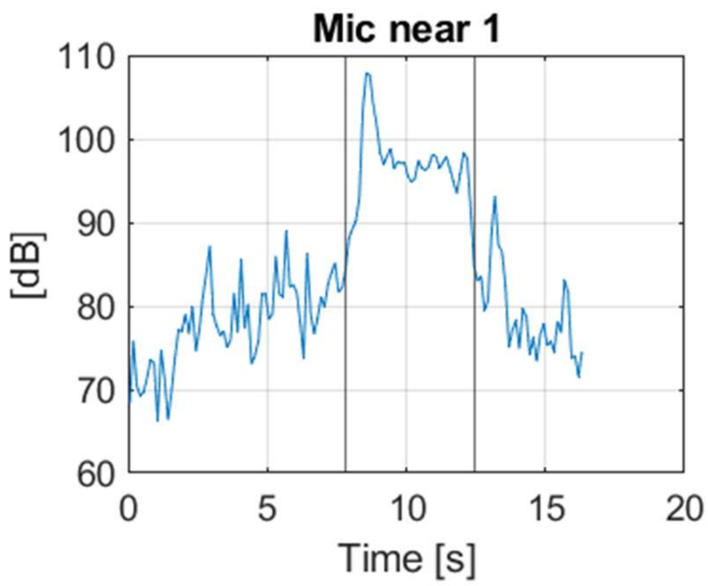
```
% A-weighting filter
weightFilt = weightingFilter('A-weighting', 'SampleRate', M1.fsamp);

M1.Dati = weightFilt(M1.Dati);
```



Experimental layout

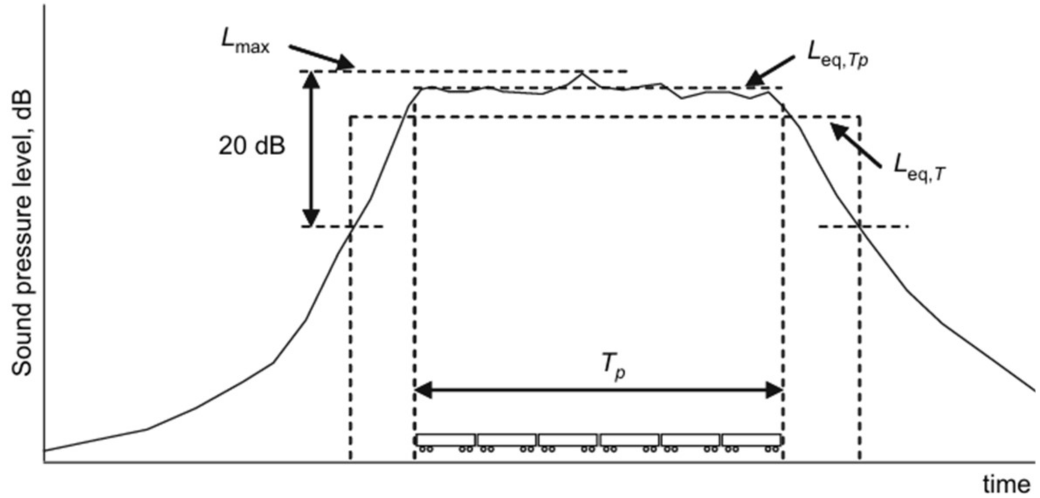
- The pressure signal of the microphone can then be converted into SPL by considering the root mean square value in rectangular windows of T=0.125 s without overlap. The time value in which L_{Max} appears can be identified.



- Then, t_1 and t_2 can be defined as the times in which a first decay of 20 dB is found starting from the L_{Max} time.

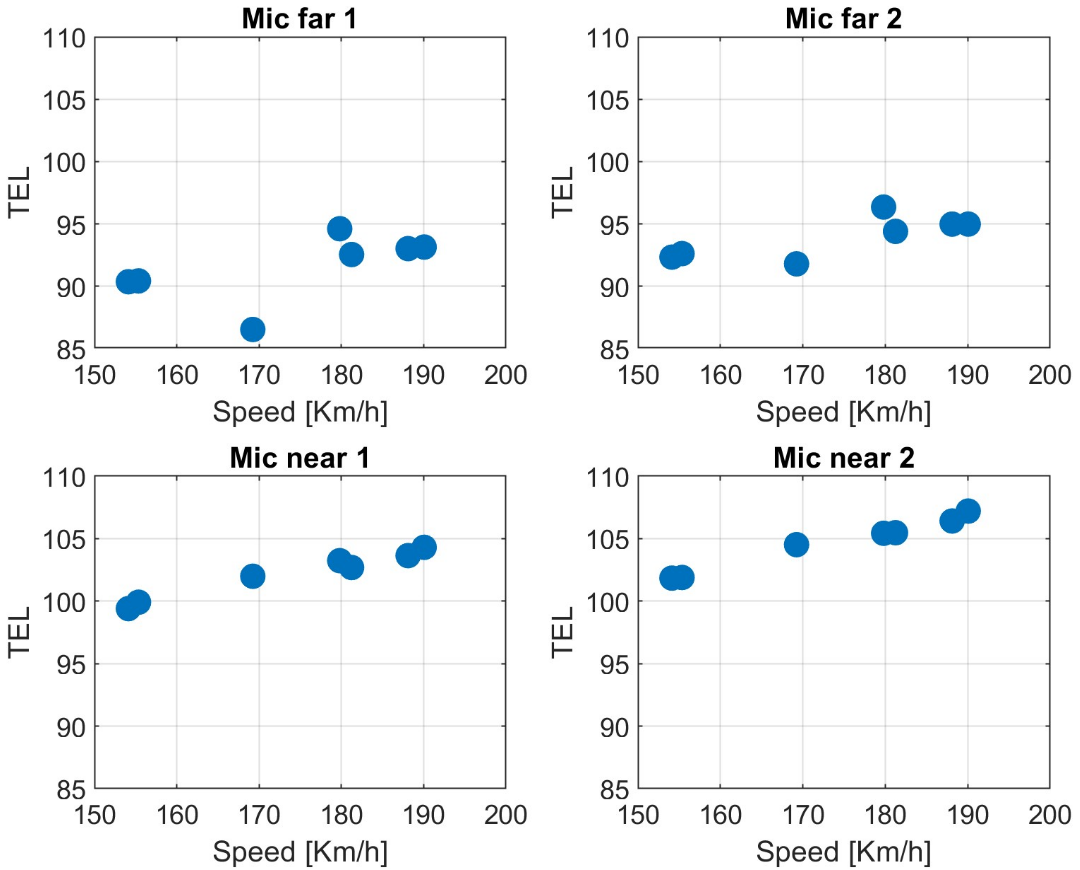
- The TEL value can be calculated.

$$\mathrm{TEL} = 10\log_{10}\left(\frac{1}{T_p}\int_{t_1}^{t_2}\frac{p_A^2(t)}{p_0^2}dt\right)$$



Experimental layout

The correlation between TEL values for far and near microphones can be plotted as function of speed considering the seven measurements performed on the test train at different speeds.



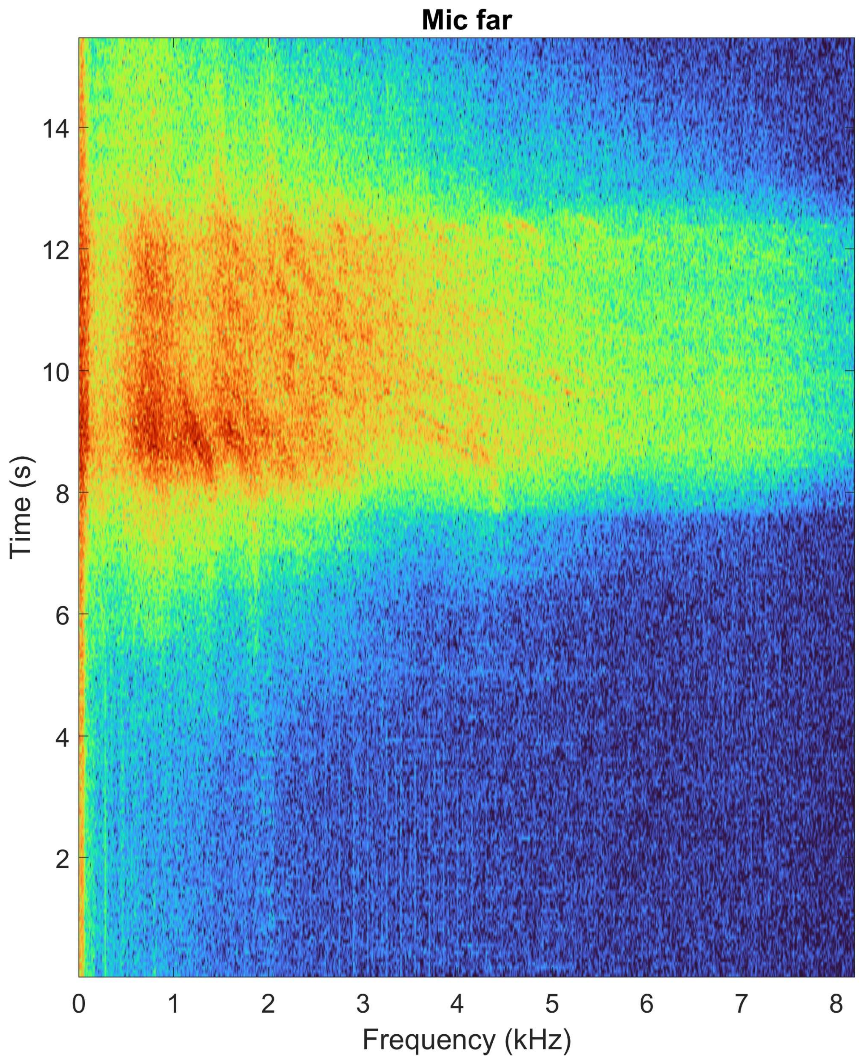
Assignment

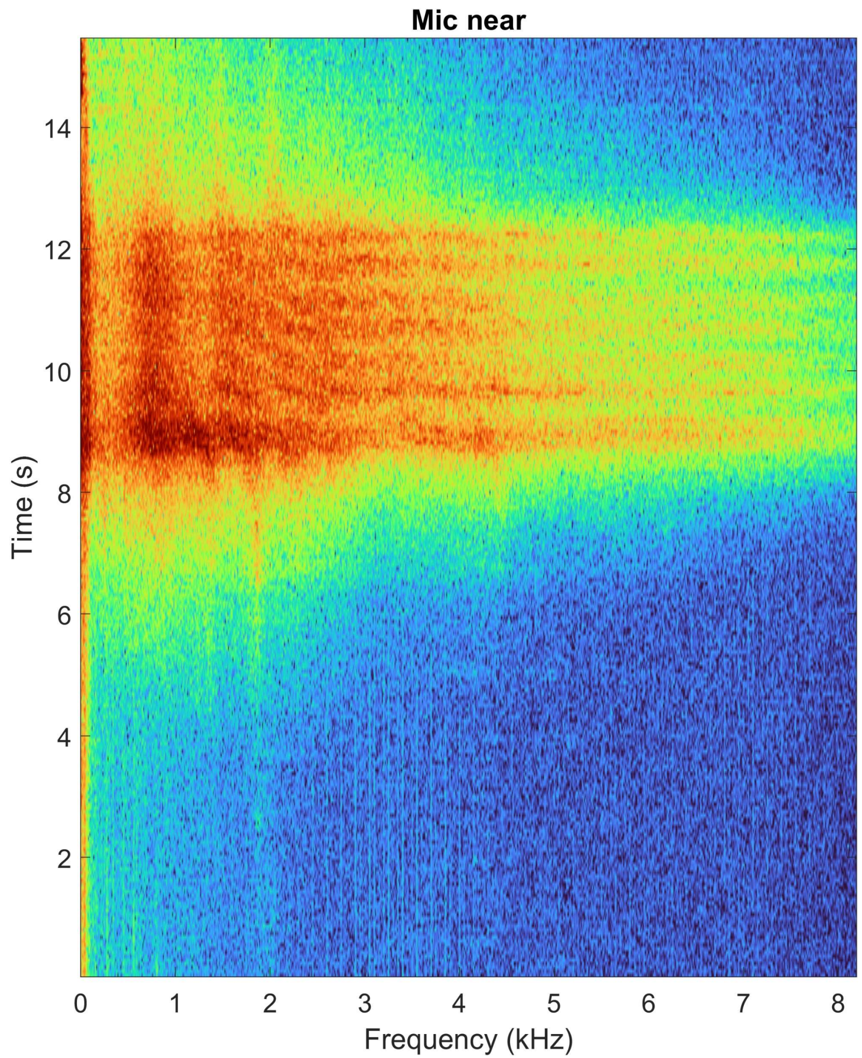
- Choose a single pass-by acquisition and show the overall post-process to obtain the TEL value according to the standard.

- Compare different TEL values obtained at different speeds.

- BONUS: compare the spectrogram of the far and near microphone. Propose hypotheses on the main sources of exterior noise.

Assignment-BONUS





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