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Prediction of ground-borne vibrations from Copenhagen Metro

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The need for additional infrastructure in densely populated urban areas has during recent years extended the use of railway traffic and in particular metros and subways. The ground-borne vibrations induced by the operation of these metros and subways often challenge the environmental regulations for acceptable comfort in the neighboring buildings. Therefore to ensure acceptable vibration comfort, a design of mitigation is needed. This is a challenging exercise of re-distributing the train-induced energy between low- and high-frequency content.
In the following the COWI A/S developed prediction model is provided. The model is based on experience from working with metros in Copenhagen and Oslo, urban rail tunnels in Malmö and London, light-rails in Denmark, as well as high-speed rail tunnels at the lower Inn valley, Austria.

This developed prediction model for the vibration and structure-borne noise is based on transfer functions. The model relies on a statistical approach to a large pool of measurements, which enables the estimation of the vibration and the structural-borne noise level at a particular building floor. The transfer functions used in this model are derived from measurements at several geological locations and several types of buildings, representing the geology and the buildings along the alignment of future projects. When using this tool for designing vibration mitigation, it is typical done by optimizing the complete track system insertion loss to match the unique combination of site-specific geology and building. Hereby the final track design will ensure the operation meets the governing noise and vibration requirement. The following example of model estimations is provided for Cityringen, Copenhagen Metro, Denmark. However, the method is general and is also applicable for high-speed lines, trams, and light rail trains.

1 Introduction

This paper describes the COWI developed model that has been used to estimate the vibration levels for both the activities related to the construction of the Copenhagen Metro and its operation. The outcome of the calculations predicts the vibration comfort and structure-borne noise levels for each floor of all the buildings next to the alignment.

The model is based upon classical empirical assumptions of frequency-dependent transmission functions from a source to a receiver subdivided into equally dominating components being: train to track, track to ground, dissipation through the ground, ground to the foundation, and from foundation to the specific floor. Each component of the empirical model is calibrated to the considered alignment by the use of full-scale vibration measurements. The measurements are conducted at each vibration significant type of geology and building. In this way, the outcome of the model is geologically and building types consistent with the considered alignment. The geological measurements can also used to convert the train vibrations characteristic into site-specific train vibration. The model predicted vibration comfort and structure-borne noise levels, are compared with recommended limits for apartments, offices, and rooms used for other purposes according to the use at this alignment. If unacceptable comfort is estimated, the associated track system will be updated to ensure the best value for money mitigation for this specific vibration characteristic. The results of the model are presented as graphical representations such as vibration maps of the areas along the alignment showing maximum estimated levels for each building or staircase. In addition, and if relevant, illustration of building facades showing estimated levels for each floor and in case of construction works the number of weeks exceedings can be expected.

The background for the COWIs methodology on which the prediction process is based, as well as the advantages of its application, is provided in the following.

2 Methodology

In general, the methodology for vibration estimating follows a three-staged mapping plan for the operation of the Copenhagen Metro:

- (Step 1) Based on visual inspection and local building register all buildings within a 200 m area from both the alignment and other planned works are mapped to identify properties, functions, and current conditions. To only focus on relevant areas a first initial calculation with conservative assumptions is carried out. Depending on the specific project this initial investigation may involve a large number of buildings. For the planned Copenhagen Metro this first step included 11.546 buildings for an approximately 15 km twin-tube tunnel alignment.

  To identify the areas where the comfort level is estimated to exceed the limits maps are used to visualize the estimated vibration levels. An example showing structural-borne noise estimates from the Copenhagen Metro is shown in Figure *1*. Initially, a large number of buildings were estimated to exceed the ruling limits by 2 – 4 dB.

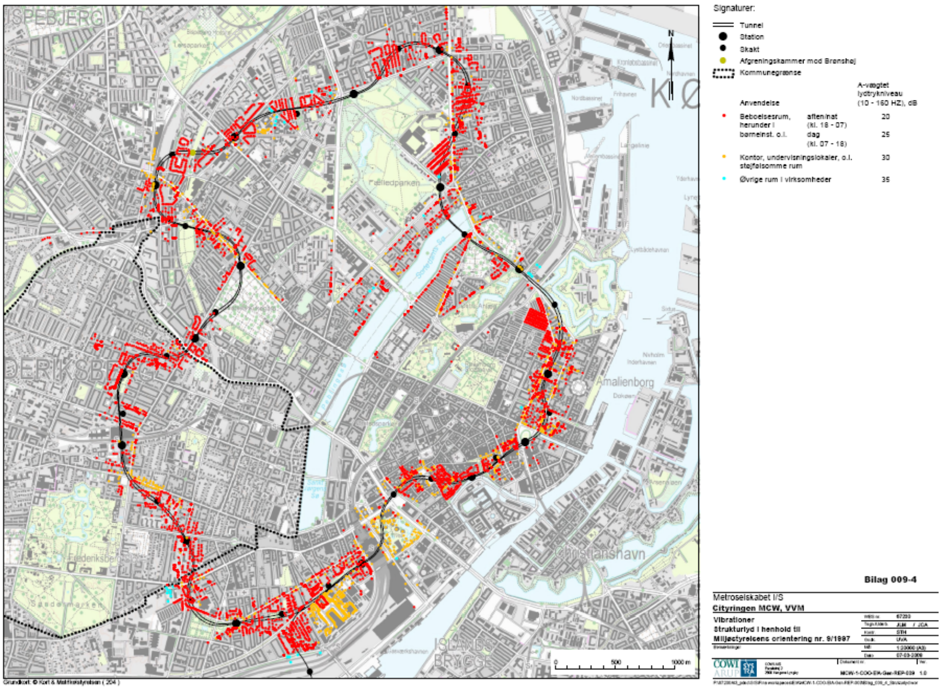

Figure 1: EIA Copenhagen Metro, 2008: Structural-borne noise estimates along the alignment.

- (Step 2) The identified focus areas are re-calculated with more accurate transfer functions. In this project, these calculations were used for specifying the Tender requirements for a track system capable of meeting all environmental regulations inside the buildings. Meaning, that in this case the calculation was done backward from having an acceptable comfort at all buildings surrounding the alignment then applying the relevant transfer functions until the estimate was traced to the Metro tube. Thereby setting the maximum train and track vibration limits at the tunnel wall. An example of such a train and track vibration limit is shown as a vibration spectra at a tunnel wall in Table *1*.

Table 1: The vibration source spectrum limit on a tunnel wall.

1/3 octave center frequency [Hz]	Vibration strength at tunnel wall [dB re 10^{-6} mm/s]	1/3 octave center frequency [Hz]	Vibration strength at tunnel wall [dB re 10^{-6} mm/s]
1	88	20	77
1.25	88	25	78
1.6	88	31.5	83
2	88	40	88
2.5	89	50	71
3.15	94	63	68
4	93	80	69
5	96	100	74
6,3	90	125	81
8	87	160	85
10	84	200	78
12.5	82	250	77
16	85	315	62

This Tender estimate still had a non-neglectable amount of uncertainty due to the predicted behavior and variation of the actual geological conditions. Therefore the specified maximum allowed vibration levels at the tunnel walls needed to be revised based on measurements conducted inside the raw tunnel. Different sections along alignment needed different mitigation. In the tender documents, it was estimated that additional mitigation was needed at approx. 5% of the track alignment (±100%).

The vibration measurements were carried out by using a large seismic vibrator generating vibrations and measuring the transmission through the soil and inside the buildings. This enables calibration of the model by geologically consistent input and proper dynamic response of the buildings within the considered areas along the alignment.

It is also investigated if buildings could benefit from minor changes in the alignment giving a larger distance between the buildings and the tunnel.

- (Step 3) The final decision on the optimal track mitigation in the tunnel was made based on the calibrated model including the vibration measurements in the raw tunnel as described in section 4. Hereby the model uncertainty can be reduced to 3 dB.

3 Empirical model for prediction of vibrations

The model described in this section is, in essence, a data-driven model. This implies that the vibration nuisance and the structure-borne noise estimates are based on the analysis of a variety of measured datasets, as described below. In this regard, the underlying basis behind the model formulation is that, given a set of explanatory variables, appropriate datasets are selected and analysed to obtain vibration nuisance and structure-borne noise estimates. In particular, the explanatory variables included in the model are the train type, the track type, the track elevation, the train speed, the geological parameters for the geological damping model, the distance between the train track and the building under consideration, the building type, the dominating natural frequency of the floor under consideration, the length of the train and the number of train passages per 10 min. Given the data-driven nature of the model, it is noted that the model estimates rely on the quality and the representativeness of the different datasets used. In terms of model applications, the model is intended for assessing vibration nuisance in relation to existing well-established comfort thresholds.

The mathematical formulation of the model is based on classical empirical formulations for predictive vibration models ([1] Madshus et al., 1996; Ziegler, 2005). This leads to the addition of frequency-dependent transmission loss functions from a source to a receiver in order to estimate vibration levels from passing trains in a building as per the expression

$$L_{aj} = L_{ak} + TL_h + TL_g + TL_b + TL_e \quad (1)$$

where:

L_{aj} calculated acceleration at a given building's floor in a logarithmic scale (1/3-octave spectrum).

L_{ak} source strength of the train combined with track and local geology in a logarithmic scale (1/3-octave spectrum).

TL_h correction for the train velocity dependence in a logarithmic scale (1/3-octave spectrum).

TL_g correction factor for vibration propagation throughout the geology in a logarithmic scale (1/3-octave spectrum).

TL_b correction factor for coupling loss at the building's foundation level in a logarithmic scale (1/3-octave spectrum).

TL_e correction factor for vibration transmission from building's foundation to a particular building's floor in a logarithmic scale (1/3-octave spectrum).

All acceleration levels are measured in the vertical direction, expressed in m/s^2 and duly converted into 1/3-octave spectrums by considering the root mean square (RMS) value of fast Fourier trans-form spectra within limited frequency intervals. All parameters in Equations 1 and 3 are obtained by way of the expressions

$$L_{ak} = 20Log_{10}\left(\frac{a_{ak}}{10^{-6}m/s^2}\right), \quad TL_x = 20Log_{10}(F_x) \quad (2)$$

where a_k is the measured source strength spectrum at 7.5 m from the train center-line, F_x refers to the transfer function in a linear scale of a quantity x, x representing the parameter subscripts h, g, b, e and an described in equations (1) and (4).

Error! Reference source not found. shows a graphical representation of how the different model terms relate to the different locations from the vibration source (i.e. the train) to a house floor. Equation 1 can be rewritten on a linear scale to calculate the resulting KB-weighted acceleration at a location j

$$a_j(f) = a_k(f) \cdot F_h(f) \cdot F_g(f) \cdot F_b(f) \cdot F_e(f) \cdot a_{KB}(f) \quad (3)$$

where f is a variable to represent the central frequency of the different spectrums expressed in a 1/3 octave representation and $a_{KB}(f)$ is the term corresponding to the central frequency f of the KB-weighting filter. $a_j(f)$ is the calculated acceleration at a given building's floor, $a_k(f)$ the source strength of the train, $F_h(f)$ a correction factor for the train velocity effect, $F_g(f)$ a correction factor for vibration propagation throughout the geology, $F_b(f)$ correction factor for the coupling loss at the building's foundation level and $F_e(f)$ correction factor for vibration transmission from building's foundation to a particular building floor. All variables in equation (3) and in equation (5) are expressed in a 1/3 octave representation.

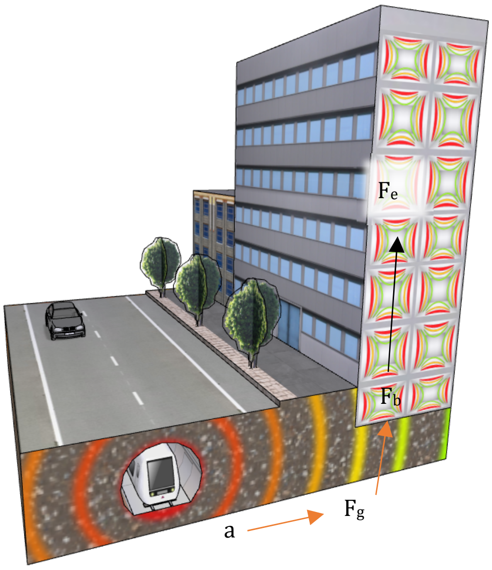

Figure 2: Principle of the vibration model during the operational phase.

It is assumed that the datasets used to characterize the terms $F_b(f)$ and $F_e(f)$ represent the characteristics of the different building and floor types included in the model. However, larger datasets would enable a more refined characterization, leading to better estimates. It has to be noted that $a_k(f) \cdot F_h(f)$, $F_b(f)$ and $F_e(f)$ are considered as random variables characterized by the different measurements performed. In contrast, $F_g(f)$ and $a_{KB}(f)$ are deterministic variables.

The same approach as the one described in the above section is used for calculating the structural born noise as:

$$L_{anj} = L_{aj} + TL_{anj} \tag{4}$$

Where L_{aj} is the un-weighted acceleration level on a floor in a logarithmic scale (1/3-octave spectrum). TL_{anj} transfer function from floor vibrations to structural-borne noise in a room in a logarithmic scale (1/3-octave spectrum).

Equation 4 on a linear scale is

$$a_{n,j}(f) = a_k(f) \cdot F_h(f) \cdot F_g(f) \cdot F_b(f) \cdot F_e(f) \cdot F_n(f) \tag{5}$$

where $a_{n,j}$ is the calculated structural-borne noise spectrum at a location j and F_n is a transfer function between acceleration levels at a building's floor and the corresponding structural-borne noise level.

4 Vibration measurements

The prediction model described in chapter 3 uses the transfer functions, which are derived from measurements at several geographical locations and building types, representing the geology and the buildings along the Copenhagen Metro alignment. The measuring locations have been chosen based on the local variations of geological conditions, building types, vertical alignment of the tunnel, and the governing environmental regulations. Vibration transmissions were measured between the surface, see

Figure *2*, and the raw tunnel, see Figure 3. The generated vibrations in the raw tunnel propagate through the soil, into the building foundations, and inside the apartments, offices, or rooms. Therefore by measuring the properties of the vibrations at each step the corresponding transmission can be calculated.

Figure *2*: COWI's own Minibuggy seismic shaker (left) offers 6 tons output force for predefined vibration excitations. This includes excitations over a frequency range between 8 and 315 Hz. Responses measured inside a building (right) located at Carit Etlars Vej in Copenhagen.

The vibration excitations are conducted on the surface to gain the transfer functions for representative buildings along the alignment. Once the raw tunnel was constructed, the vibration excitations were carried out inside the tunnel, and the associated dynamic responses were measured on the surface as well as inside the buildings of interest. The transfer functions for ground transmissions are obtained from the raw tunnel to the surface.

Figure 3: Vibration excitations carried out on concrete plinth in the raw tunnel. The shaker piston is seen on the plinth in the center

Each transmission is derived by carrying out measurements at three locations inside the tunnel below the selected building and measuring the response at the surface and inside the building as illustrated in Figure 4. The locations inside the tunnel are defined as:

- #1t) Inside the tunnel at the location with the shortest distance to the selected building,
- #2t) At a position 1.5 x (the shortest distance between the relevant track and building foundation)
- #3t) At a position 2.0 x (the shortest distance between the relevant track and building foundation)

The vibrations inside the tunnel are measured on the tunnel wall (1.2 m above Top Of Rail) and on the tunnel floor (0.75 m from the middle of the track). Similarly, the response on the surface is measured at four locations, namely:

- #1s) Building foundation,
- #2s) Surface level, 5 m from the foundation,
- #3s) In the middle of a room located on the ground floor,
- #4s) In the middle of a room located on the upper floor.

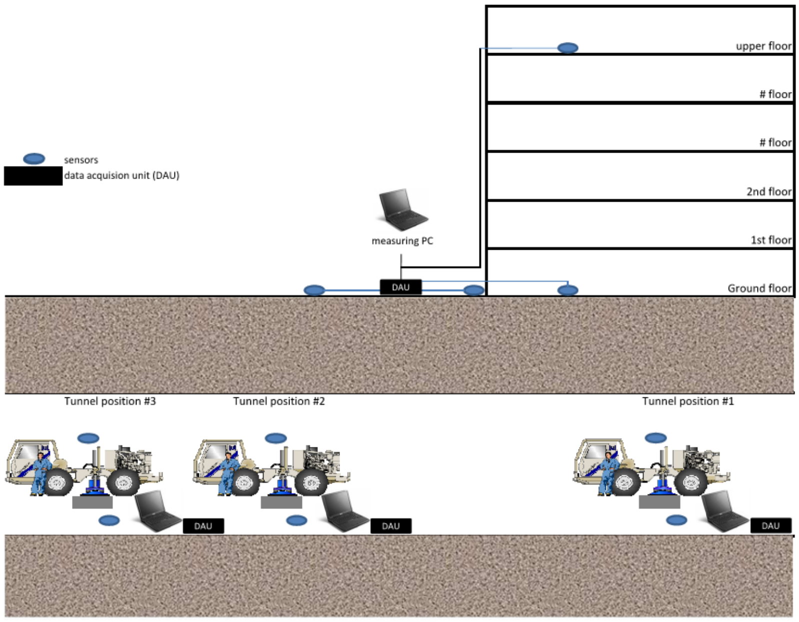

Figure 4: Illustration of the measurement campaign to define transfer functions.

The geological model is defined for the site-specific calculations from these measurements. In addition, the measurements gathered by the sensors inside the building are used to verify the full chain of the model predictions.

5 Results of railway traffic ground-borne vibrations

The estimated acceleration and structure-borne noise levels for all floors of all buildings included in the assessed area are presented on a color-coded vibration map identifying the maximum acceleration level in each building. In case recommended values are exceeded in any building, it is identified and the frequency range in need of special attention is pointing out. A sample of the vibration map is shown in Figure 5 below.

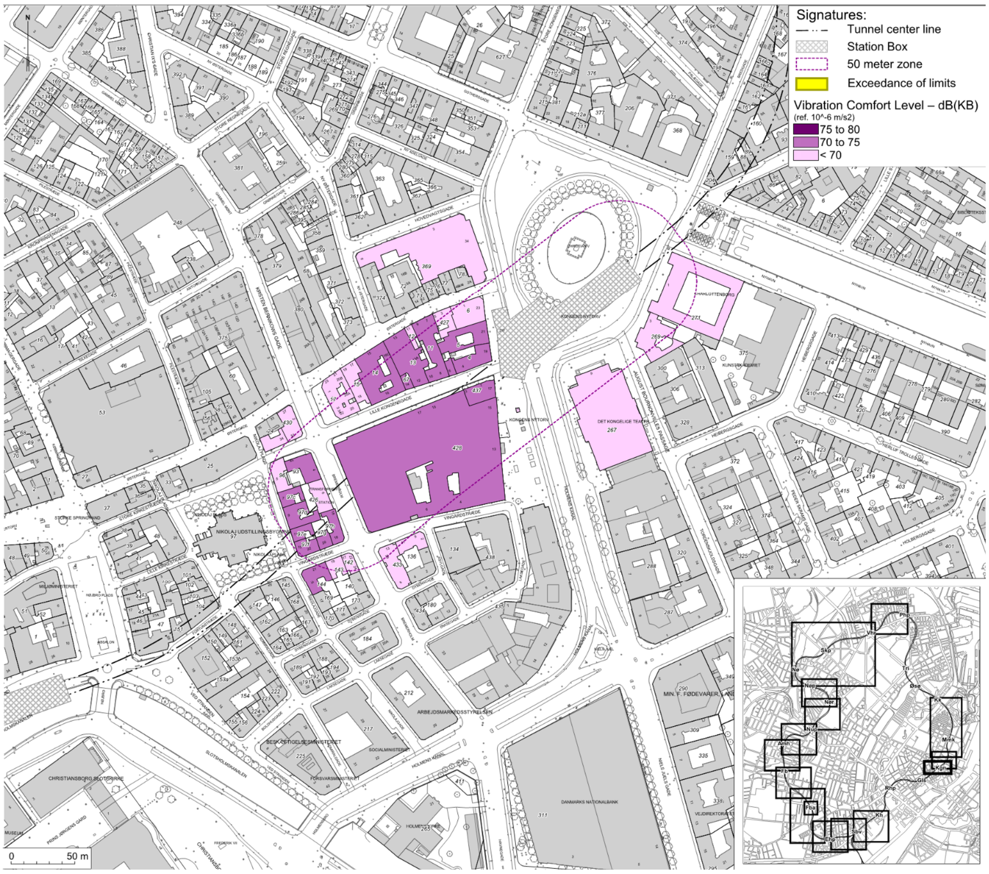

Figure 5: Vibration comfort values for the area next to the planned metro station.

The predicted vibration comfort and structure-borne noise levels are compared to the relevant requirements and thereby the track stretches requiring mitigation are identified. The insertion losses for the track system are implemented into the empirical model and thereby verifying that the final track design meets the requirements. Besides metro, the method is general and is also applicable for high-speed lines, trams, and light rail trains.

References

[1] Madshus C, Bessason B and Harvik L (1996) Prediction model for low frequency vibration from high speed railways on soft ground, Journal of Sound and Vibration 193(1): 195-203.