

# Monitoring sound exposure by real time measurement and dynamic noise map

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## Summary

In contrast to traditional noise maps like those produced in the framework of the European Commission's Environmental Noise Directive, dynamic noise maps are introduced in this work. Dynamic noise maps are based on a combination of noise monitoring networks and a long-term averaged noise map. The proposed interpolating model is inspired by land-use regression models, which are commonly used in air pollution monitoring. Obvious noise indicators like equivalent sound pressure levels can be mapped with a time resolution down to 15 minutes. Dynamic noise maps could therefore provide a more complete picture of the city noise climate and lie closer to human observations. An important prerequisite is that a reasonably good long-term averaged model for the sound indicators in the area under study is available. Temporal variations arise from changes in the noise source and variations in the propagation of sound. In addition, the presence of sources that are generally not considered in noise maps often add to the dynamic character. The interpolation model tunes the source characteristics and propagation aspects on the basis of measurements providing a prediction of the momentary sound pressure levels at locations where no measurements are available. The proposed dynamic maps could be well suited to predict noise-related effects where the temporal aspect is important like annoyance and sleep disturbance.

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## 1. Introduction

Strategic noise mapping has been implemented in many European countries since 2002 and the noise climate and its effect on people are commonly analysed based on these maps [1, 2, 3, 4, 5]. Monitoring campaigns [6, 7] have shown that the deviations between the calculated and measured acoustical indicators are small at directly exposed locations, but might become very large at locations outside the direct sound path, especially at highly shielded locations. In addition, some sources are not available in the data sets used to produce the strategic maps, for example traffic on minor roads or industrial and recreational sound sources. Moreover, the dynamic changes of (temporary) sources are not well represented by the annually averaged sound power. Inaccuracy could also be introduced by assumptions of the calculation models and their simplification of the reality; for example the effect of intermediate canyons [8], the presence of noise-reducing measures like e.g. green roofs [9] and complex ter-

rain data [10, 11]. These aforementioned considerations form the starting point to develop more accurate and dynamic maps. A recent dynamic mapping strategy assumes that the spatial attenuation is independent of time and the dynamic sound level at receivers can be obtained by only updating the source power in short time intervals [12]. However, this method fails when meteorological effects cannot be ignored or when the errors in the propagation model are significant. Another method consists in measuring noise levels instantaneously at many immission points using mobile measurements and then interpolating these to make a dynamic map [13]. Needless to say, the accuracy of this method depends on the density of the measured positions. Besides, its spatial accuracy is usually poor. Considering reducing the propagation errors, source errors and tuning the map by measurements, a model-based interpolation method will be presented. The basic assumption underlying this model-based interpolation is that there is a reasonably good model for the sound indicators in the area under study but that this model is not very accurate for instantaneous (basic time frame is 15 minutes) level predictions. The interpolation method will tune the source and propagation characteristics on the basis of measurements to

improve predictions at locations where no measurements are available. This paper is organized as follows: 1) introduce conceptual layout; 2) analyse the theoretical achievement; 3) implement the model with a case study.

## 2. Conceptual layout

### 2.1. Basic layout

The sound level  $L_f(p, t)$  is defined in a general sense as an indicator and  $f$  is the octave band. It depends on place  $p$  and time  $t$ .  $L_f(p, t)$  is written as a sum of several contributions:

$$L_f(p, t) = 10 \log_{10} \sum_i^{N_s} \sum_j^{N_h} 10^{0.1[L'_{W,f,i}(t) - A'_{f,i,j}(p)]} \quad (1)$$

where the sources are labelled by index  $i$  and are indexed by  $j$  which allows for different propagation paths between the  $i^{th}$  source and location  $p$ ;  $N_s$  is the total number of sources and  $N_h$  is the total number of propagation paths.

The actual values for sound emission  $L'_{W,f,i}$  and attenuation  $A'_{f,i,j}$  now have to be obtained from their theoretical value  $L_{W,f,i}$  and  $A_{f,i,j}$  and the measured levels  $L_{f,meas}(p_{meas}, t)$ . For this, it is assumed that the actual value deviates only by a "small" amount from its theoretical value, as:

$$L'_{W,f,i} = L_{W,f,i}(t)(1 + \epsilon_{f,i}^{t-1}) \quad (2)$$

$$A'_{f,i,j}(p) = A_{f,i,j}(p) + \delta_{f,i,j}^{t-1} \quad (3)$$

Both  $\epsilon_{f,i}^{t-1}$  and  $\delta_{f,i,j}^{t-1}$  are functions of frequency and time, but can be functions of several other parameters. The number of parameters that can be introduced depends on the number of measurement locations that are available in the study area and their distribution over space. Extracting  $\epsilon_{f,i}^{t-1}$  and  $\delta_{f,i,j}^{t-1}$  will be done by comparing with the measurements  $L_{f,meas}(p_{meas}, t)$ .

### 2.2. Source categorization

Inspired by the land-use regression modeling and in order to limit both the number of terms in the sum,  $N_s$ , and the degrees of freedom in  $\epsilon_f$  that could possibly be resolved with the typical number of sound observatories currently available, traffic sources are categorized. To be able to resolve the solution of  $\epsilon$  at time  $t$  and a specific frequency  $f$ , the number of source categories should typically be less than the measurement positions.

Categorizations could depend on traffic intensity, speed limit, or other categorization methods. Initially it is proposed to work with intensities and the use of 4 categories ( $< 600$ ,  $[600, 1200]$ ,  $[1200, 6000]$ ,  $> 6000$ ). All streets with traffic within these ranges are grouped to a single source. The sound power per unit length emitted by all the streets within the same category is assumed equal. In this case one can calculate the contribution of the distributed source to each receiver position and separate emission from attenuation as discussed above in the general layout. The disadvantage of this approach is that subtle known differences in traffic intensity and speed will not be considered.

For other sources, e.g. playgrounds, single point source and propagation can be calculated since these sources will mainly have a local influence.

After categorization, equation 1 can be rewritten as:

$$L_f(p, t) = 10 \log_{10} \left[ \sum_{i=N_0}^{N_1} \sum_j^{N_h} 10^{0.1L'_{W,f,i}(t) - A'_{f,i,j}(p)} + \sum_{i=N_1+1}^{N_2} \sum_j^{N_h} 10^{0.1L'_{W,f,i}(t) - A'_{f,i,j}(p)} + \vdots + \sum_{i=N_n+1}^{N_s} \sum_j^{N_h} 10^{0.1L'_{W,f,i}(t) - A'_{f,i,j}(p)} \right] \quad (4)$$

Every double sum group on the right-hand side of the equation indicates a source category, which implies that one can separately calculate noise maps for each source category and sum them up to obtain the final value. As mentioned before, the total number of categories should be less than the number of measurement positions.

### 2.3. Propagation paths

In the basic model three propagation paths are included for road traffic noise sources:

- direct sound, that is the contribution without propagation over buildings, but including reflections.
- diffracted sound, that is the contribution caused by multiple reflections in the street canyon and diffractions over buildings.
- turbulent scattered sound

Each of these contributions will have its own correction  $\delta$  which is independent of the sources.

In this study, 1) the spectrum of the traffic source powers are assumed to be accurately calculated; 2) the frequency dependence of the methods to calculate the direct sound, diffracted sound and turbulence

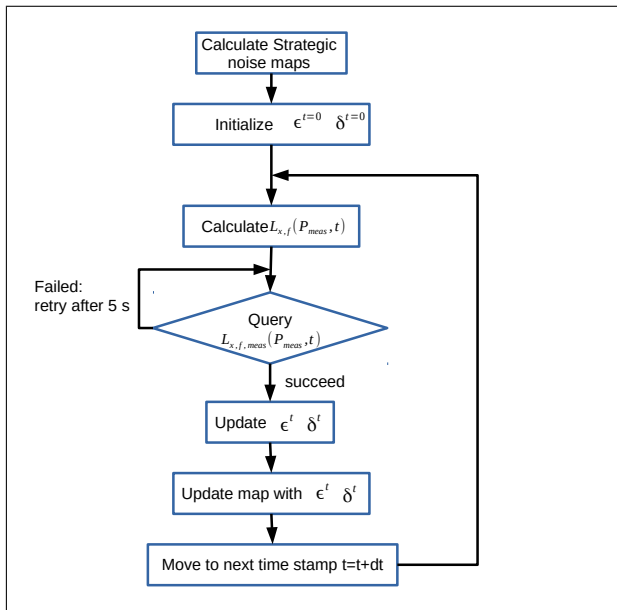


Figure 1. Implementation flow of the model.

scattering sound would need second order corrections only. Under these two assumptions, the dependence on frequency of delta and epsilon can be removed. If more measurement positions were available, the need for these assumptions could be reconsidered.

### 3. Implementation

The overall system for calculating dynamic noise maps in real time contains the following steps 1) calculate the noise map for propagation path “direct”, “diffract” and “scatter” for all the categorized sources and extra sources; 2) query the server for measurement data at the start time; 3) run the optimisation method to obtain  $\epsilon$  and  $\delta$  and update the noise maps; 4) move forward by one time stamp (in this case the time step is 15 min). A flow-chart is shown in figure (1).

### 4. Case study

A case study in Katendrecht, a district of Rotterdam, the Netherlands, is used to validate the model. In this study, the traffic sources are grouped to four categories and industrial noise (there is an industry area to the south of the peninsula) is represented by 4 separate point sources with the same source power spectrum. The categorized spectrum of  $L_{Aday}$  is shown in figure (2). The spectrum of the industrial source power is estimated from the measurements at the closest location, which is however still in the far field. The assumed spectrum is: 97.3, 101.5, 106.0, 109.2, 108.2, 101.1, 94.7, 53.5 dB A from 63 Hz to 8000 Hz central frequencies.

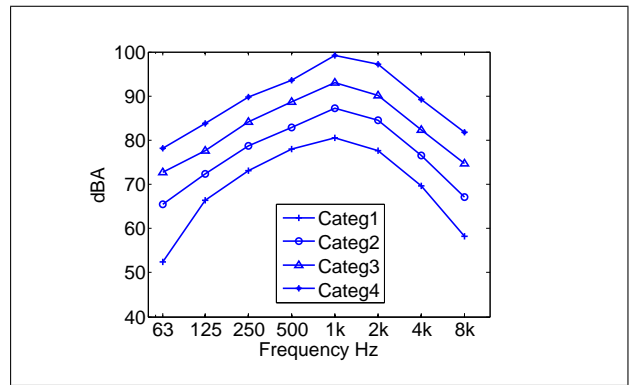


Figure 2. Spectrum of the categorized traffic sources:  $L_{Aday}$ .

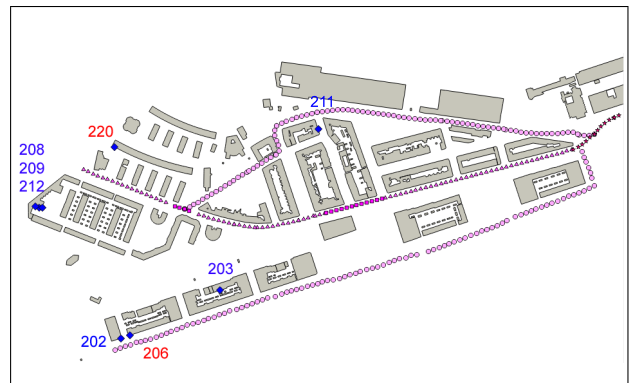


Figure 3. Measurement positions, with marking of the validation positions 206 and 220. The circles are the traffic sound sources from category 1; the triangles from category 2; the squares from category 3 and the stars from category 4.

Eight measurement stations [14, 15] are placed on the peninsula, as shown in figure (3). 6 of them are used to calculate the source correction  $\epsilon$  and propagation correction  $\delta$  and 2 of them are used to check the model. In this case study,  $L_{Aeq}$  per 15 min is extracted from the measurement station to fit this model.

#### 4.1. Parameter fitting

Based on the measured and calculated noise levels and according to the procedure mentioned in the previous section, the correction coefficients  $\epsilon$  and  $\delta$  are fitted. Results are shown in figure (4, 5, 6, 7, 8). Figures (4, 5, 6, 7 and 8) show that the “direct” path is underestimated for source category 1 to category 3 and is overestimated in category 4. The “scatter” path is overestimated, which is probably caused by inappropriate assumptions on the turbulence strength. The “diffract” path is fairly accurately calculated. The curves of the propagation corrections change slowly and smoothly, however, the source correction curve (figure (8)) has a strong diurnal pattern, implying that the original traffic pattern may not present the real situation properly. For source category 1 and 2, their

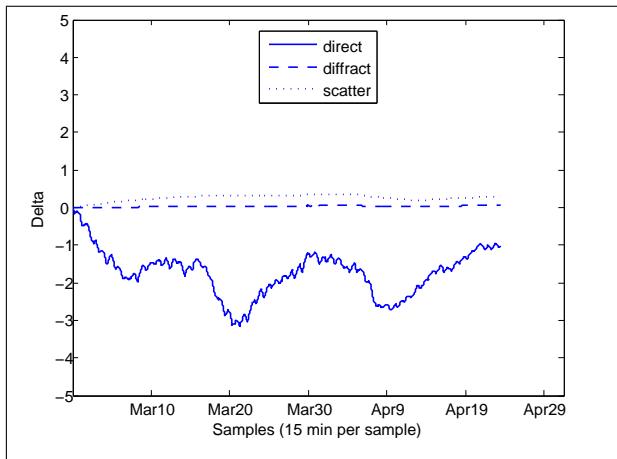


Figure 4. Source category 1. Adapting curve of the propagation term  $\delta$  for the traffic sources. “direct” indicates the propagation correction for direct sound path; “diffract” indicates the diffraction path and “scatter” indicates the turbulence scattering path.

corrections of the propagation path “diffract” and “scatter” are small compared to the “direct” path correction. For source category 3, the contribution of the “diffract” and “scatter” become dominant. According to the source positions of the case study (as shown in figure (3)), these changes imply that this model successfully captures the sound propagation properties, i.e. at locations close the receivers, the direct sound would be dominant and thus the first candidate for adaptation to reality, while at locations far from the receivers, the contribution caused by the multiple reflections and scattering would be dominant and thus primarily adapted. In figure (4), the two valleys of the “direct” path correction are mainly caused by wind-induced microphone noise, based on analysis of local meteorological data.

For category 2, 3 and even category 4 traffic sources, the effect of meteorological conditions on propagation is less clear. That is because part of the effect is translated to a change in sound power emission, as shown in figure (8). Indeed, the optimization algorithm can only distinguish between source and propagation effects in case there is a strong direct observation of the source, which is the case for category 1 traffic sources that are found close to some of the measurement locations (point 202 and 211 in Figure (3)).

#### 4.2. Results and discussion

Using the corrections based on the measurements, the final predictions for  $L_{Aeq}$ , both at the fitting locations and validation locations improve, as shown in figures (9) and (10). These figures show the distribution and cumulative distribution of the change in the error between model and measurements for a period of 45 days. Figure (10) shows that more than

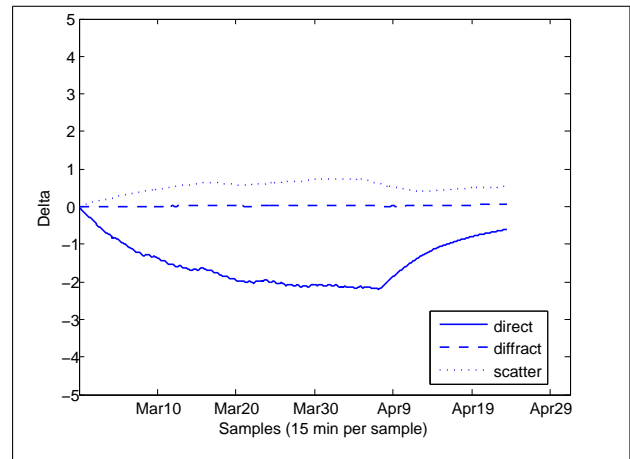


Figure 5. Source category 2

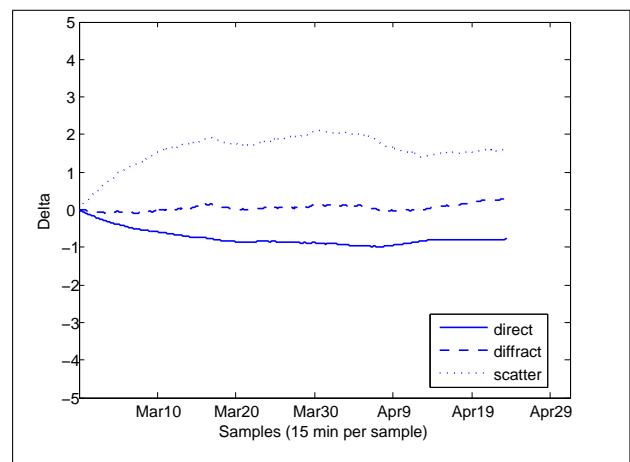


Figure 6. Source category 3

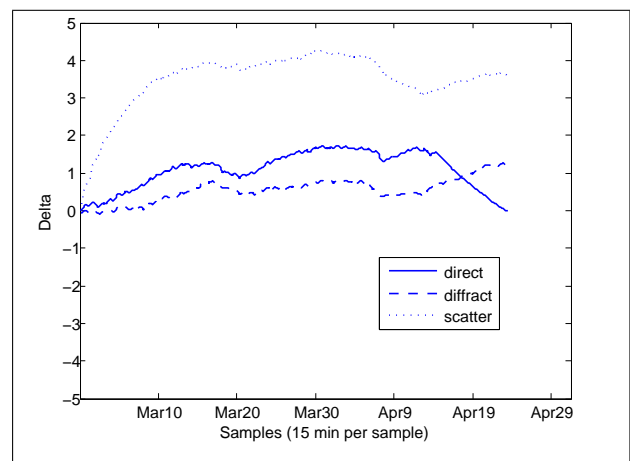


Figure 7. Source category 4

78% percent of the samples at the validation positions have better predictions after correcting. According to figure (9), improvements lie mainly between 1.8 dB and 5.2 dB.

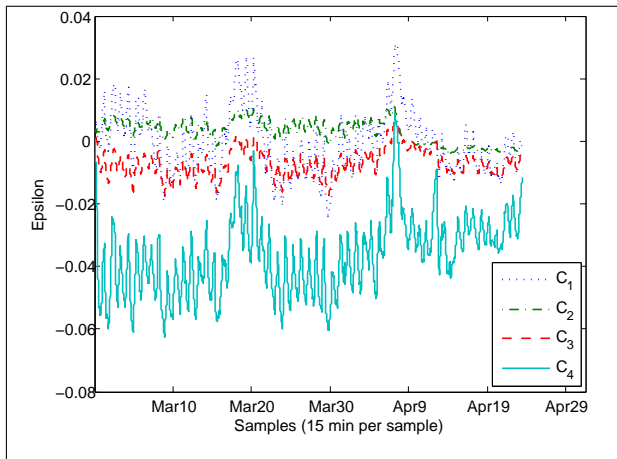


Figure 8. Adapting curve of the categorized traffic sources.  $C_1$ ,  $C_2$ ,  $C_3$  and  $C_4$  indicates the category number.

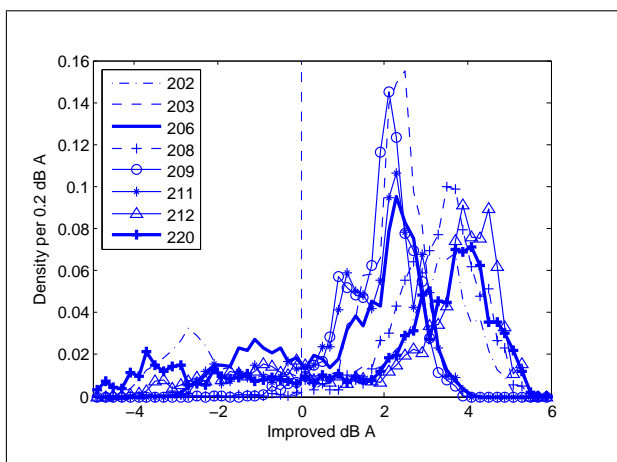


Figure 9. Distribution of the improvement. Negative values indicate that the predictions become worse and positive values indicate that the prediction is improved after correcting. The thick lines refer to the measurements used for independent checking.

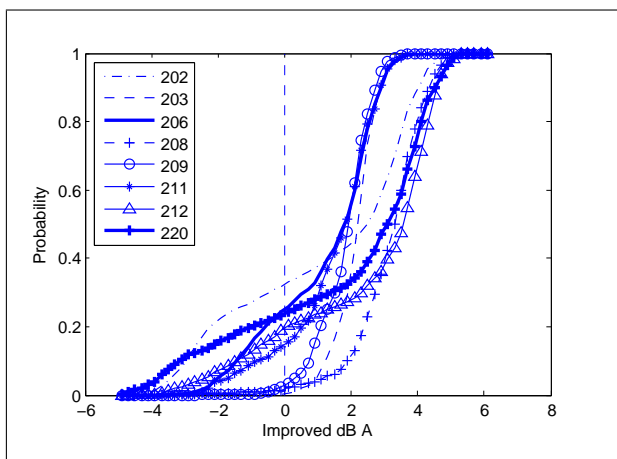


Figure 10. Cumulative probability distribution of the improvement.

## 5. Conclusion

The theoretical and practical implementation of a model-based interpolation method to calculate a dynamic noise map is presented. In this model, the sources are categorized and the contribution of different propagation paths are separated, which gives opportunity to refine the predictions in case more measurement stations or better propagation models are available. The case study proved that this method could improve the prediction in more than 78% of the 15-minute time intervals. The main improvement range is between 1.8 dBA to 5.2 dBA. Although increasing the source power and decreasing the attenuation can both increase the predicted noise level at receivers, this model can determine which of these effects play the strongest role provided that measurements less affected by meteorological conditions are available. According to the figures listed before, this model can successfully tune the overestimation or underestimation of the calculation results. Additionally, this model can efficiently update the dynamic noise map. It took less than 0.5 s in this case study with 25498 sources and 3220 receivers by Intel(R) Xeon(R) CPU E5620 2.4 GHz to obtain each updated map.

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