Model based monitoring of traffic noise in an urban district

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ABSTRACT

Noise control for an urban district starts by understanding the actual noise situation. A correct understanding is needed to take appropriate and cost efficient measures. For a noise burdened urban district, surrounded by road and rail traffic, the traffic noise as well as the annoyance has been measured. The size of the district is approximately one square km. With the help of 35 microphones, applied in a scalable sensor network, the time-varying sound levels were recorded. These results were coupled to an engineering model to obtain the sound levels for the complete district as well as to discriminate between road and rail traffic noise. Also, a data assimilation technique has been applied to increase the agreement between the measurement and model results. For example, for L_{den} sound levels the standard used source strengths for road and rail needed to be adapted to better match the sound level measurement results. In a separate paper these corrected sound levels at the façades are coupled to annoyance survey results to derive a local exposure-response relation. The annoyance survey also indicated the importance of peak levels and vibrations. This is further investigated by considering the measured noise dynamics.

Keywords: Urban sound propagation, Traffic noise, Monitoring, Noise maps, Data assimilation
I-INCE Classification of Subjects Number(s): 76.1, 73, 52.3, 52.4

1. INTRODUCTION

Traffic noise is a major source of annoyance in urban areas and reducing the annoyance is a challenge for local governments in particular. Conventionally, L_{den} noise levels in a city are calculated with the use of an acoustic engineering model and traffic data or traffic data estimates. The calculated sound levels can then be related to the amount of annoyed or highly annoyed people using standard exposure-response relations.

However, for a local urban area the situation can be acoustically complex. Especially for sound levels at façades that do not have a direct line-of-sight towards a major road. Also, the actual traffic noise can differ from the noise based standard used traffic data; so it may be preferred to use the actual source levels when determining the traffic noise in an urban area. Finally, the exposure-annoyance relation for a local situation may differ substantially from the standard relation, see for instance (1-3).

To better understand the traffic noise situation in an urban area, and to be able to decide on or to evaluate appropriate and cost efficient measures, this paper presents an "Acoustic Model Based Monitoring" technique (AMBM).

The AMBM technique is demonstrated for a real-life urban district in the city of Vught, The Netherlands, see Figure 1. In this area of approximately one square km, there are contributions from road and rail traffic noise and the annoyance is expected to be high.

Seven major sources are considered (two railways, a highway, and four roads) plus additional background noise. Based on these sources a network of 35 microphones was deployed, see Figure 2. It consists of 7 wired "advanced nodes" which measure the noise in octave bands, and 28 wireless "basic nodes" which measure the broadband sound levels, see also (4-6). For each advanced node, a wireless connection is made to 4 neighboring basic nodes. Sound levels are measured multiple times per second. It is remarked that nowadays the hardware, installation and upkeep costs are at a much lower level compared to a few years ago.

In section 2 the AMBM technique is explained in more detail: time-varying traffic noise source

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levels can be determined and then the acoustic engineering model provides the time-varying noise levels at the façades. Section 3 describes a data assimilation technique to increase the agreement between the measurement and model results. In section 4 results of the AMBM technique are shown: time-varying noise maps indicate the effects of the traffic intensity during the day as well as the noise dynamics of road and rail traffic.

Figure 1. The urban district with 7 major traffic noise sources (indicated in red) and background noise.

By averaging the noise levels to L_{den} values one can determine the annoyance with a standard exposure-annoyance relation. However, in a separate paper (7) it is shown that the standard annoyance largely differs from the *locally* derived exposure-response relation; i.e. for the same urban district as where the AMBM technique was applied so that the actual sound levels at the façades where determined.

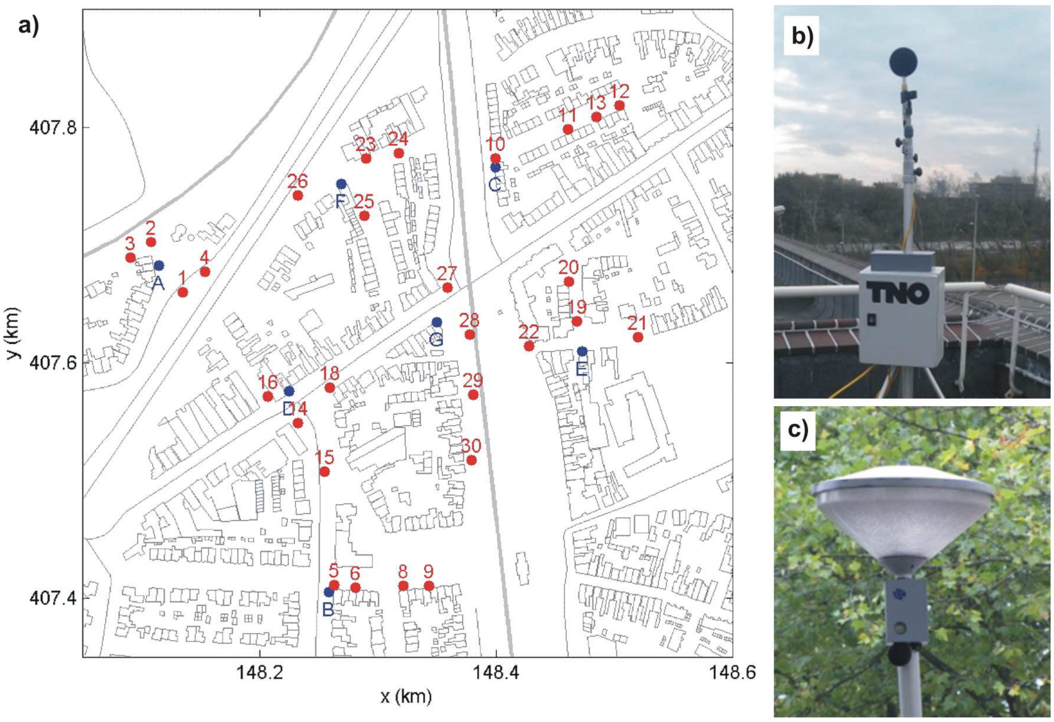

Figure 2. Overview of sensor node locations in urban district (a) with 7 wired advanced nodes (b, in blue) and 28 wireless basic nodes (c, in red).

2. ACOUSTIC MODEL BASED MONITORING (AMBM)

The use of sound maps for larger cities is prescribed by the European Noise Directive. These maps provide an indication of locations where mitigating actions should be applied. Obviously, these sound maps are a simplified representation of reality and show the yearly averaged sound levels (L_{den} and L_{night}). The AMBM technique can provide a validation of these sound levels, but it also provides more detail in time (e.g. per hour/day/week resulting in a dynamic sound map).

Figure 3 shows a comparison of conventional noise mapping and the AMBM technique. As a first step the monitoring positions are coupled to the most relevant sources (here: 5 roads and 2 railways). Next, the source strengths are estimated from the nearby observation nodes. By using different averaging times, the traffic noise source levels are obtained for different time scales.

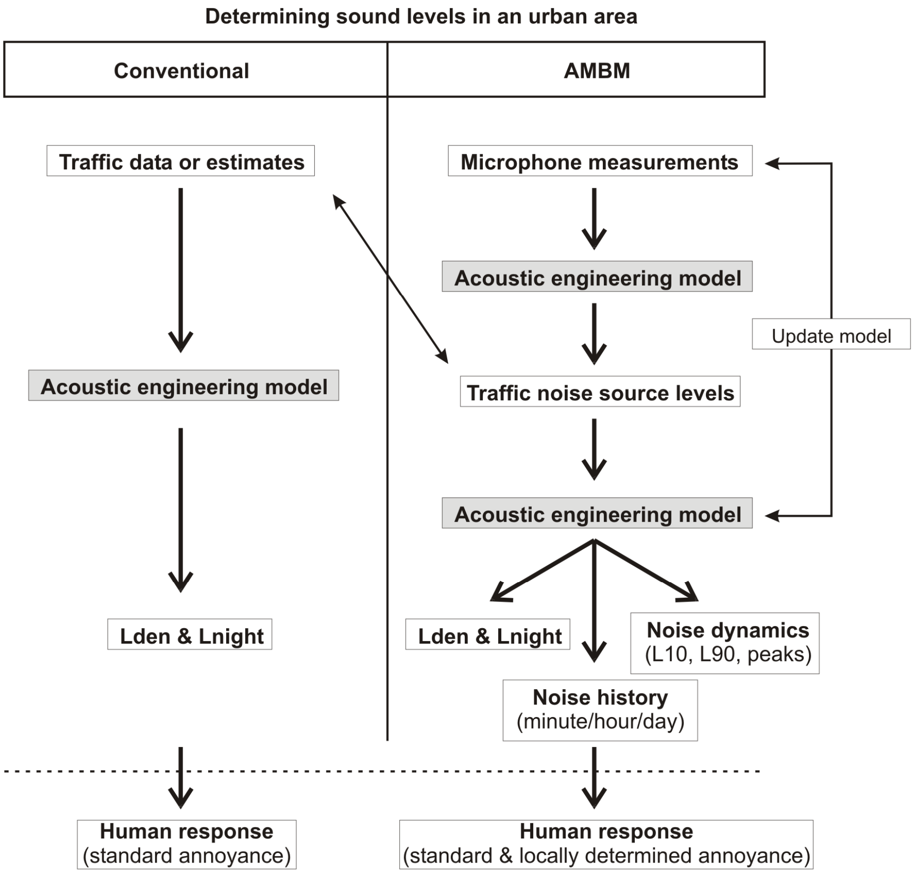

Figure 3. Flow chart to determine various sound levels and indicators in an urban area for “Conventional” and “Acoustic Model Based Monitoring” (AMBM) approach.

Next, the acoustic engineering model is applied for the whole urban area. See Figure 4 for a representation of the receiver points (left hand side) and an impression of the resulting sound levels (right hand side). Here, the sound levels represent an equivalent A-weighted sound level for one hour ($L_{A,eq(1\ hour)}$) in the morning. The contributions of the two railways, indicated with dashed lines, the highway and the other 4 roads can be clearly seen. The figure also shows the locations and sound levels at the microphones. Differences between model results and measurements can be observed. In section 3 a data assimilation method is described which takes into account the uncertainties in measurements, source levels and model results.

As the AMBM technique captures the time-varying traffic noise, the noise history for the urban area can be determined. Also, additional quantities can be derived for assessing the soundscape: peak levels, the number of events, the noise dynamics (L_{95}, L_{50}, L_{10}-L_{90}), etc.

With the use of AMBM the noise levels and noise dynamics can be determined at the façades in order to relate this to the human response. The human response has also been measured in this urban area, so a local exposure-relation could be derived. This relation has been compared to the standard relation, see (7).

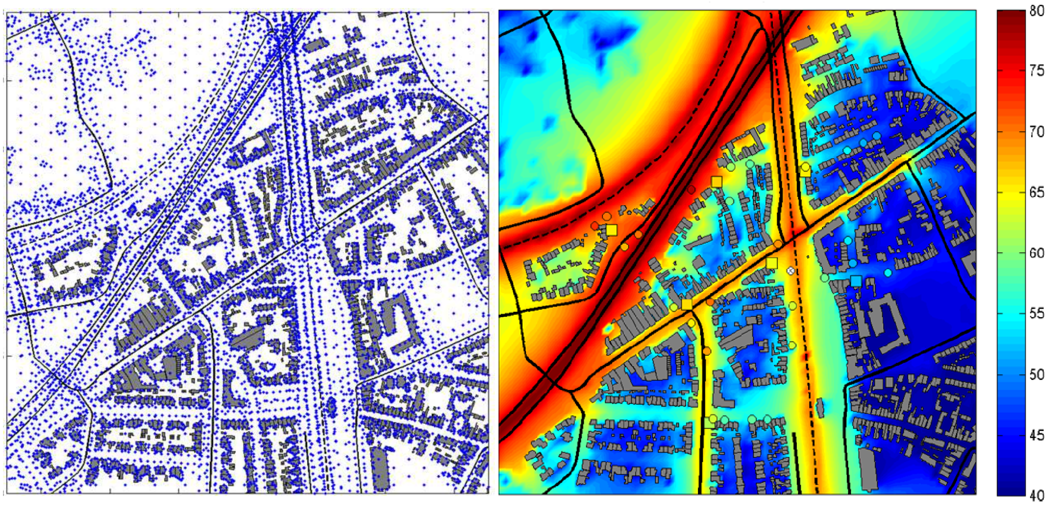

Figure 4. Left: Receiver points (in blue) for the urban area as used in the engineering model. Right: Example of calculated sound levels in dB(A) determined via AMBM using one hour of traffic noise source data.

3. DATA ASSIMILATION

The data assimilation, shortly described here, combines the simulations and observations, taking into account the uncertainties in both simulations and observations. In this study hourly averaged noise values are considered for each octave band. Note that the advanced nodes provide this octave band spectrum directly. The basic nodes provide a broadband A-weighted sound level. The spectrum of the basic nodes is approximated per sub-network by using the shape of the advanced node.

The goal of the study is to quantify the sound levels produced by the various sources using data from the observation network. To this end the source-receiver relations from the acoustic engineering model are used. For the hourly based data assimilation, first a 24 hour source level reference was estimated.

3.1 Source level estimation

For the urban area case, the 7 source strengths can be derived directly with a least squares approach of the measurements combined with the sound transfer functions of the acoustic engineering model. Figure 5 shows source level results for the highway and the north-to-south railway. The figure also shows the averaged levels for the day, evening and night for each of the available 8 days of measurements. Saturday and Sunday show lower averaged sound levels.

The source levels show a diurnal cycle, with low levels at night and high levels during the day, especially during the rush hours. So an estimate of the diurnal cycle has been made for the sources. These 'daily averaged source strengths' are calculated for each source for 24 hours. Figure 6 shows the daily averaged profile for the 7 sources and the 8 octave bands. Also shown is an estimate of the background levels (source number 8). This is based on the measured L_{90} levels (level that is exceeded 90% of the time). The L_{90} levels are averaged for the 7 advanced nodes measurement locations.

3.2 Kalman filter approach

A Kalman filter can be used to combine simulations and observations while taking into account uncertainties in both. The filter is sequential, which means that it uses only observations from current and previous times to obtain the best estimate of the current state; here, the source level. The filter performs best if it has to estimate small deviations from a reference, so for the state *x* during hour *k* one has:

$$s_k = \bar{s}_k + x_k \tag{1}$$

with s_k the source level for each source and octave band, and $\bar{s}_k$ the diurnal average source level.

For the Kalman filter the transition for the state *x* from hour to hour is used:

$$x_k = A_k x_{k-1} + w_k \tag{2}$$

with the matrix *A* the relation between current state and previous state and *w* the error in the transition model assuming a normal distribution with a zero mean and a standard deviation in dB. To obtain the

A matrix and the covariance, an autoregressive model of order one has been applied on the hourly averaged source data.

For the observations y_k one has:

$$y_k = \mathrm{h}(\bar{s}_k + x_k) + v_k \quad \approx \quad \mathrm{h}(\bar{s}_k) + \mathrm{H} \cdot x_k + v_k \tag{3}$$

with the observation operator *h* and the error *v* assuming again a normal distribution and a (given) standard deviation in dB. Here, a linearization has been applied to get matrix *H* to be able to use the (intrinsic linear) Kalman filter.

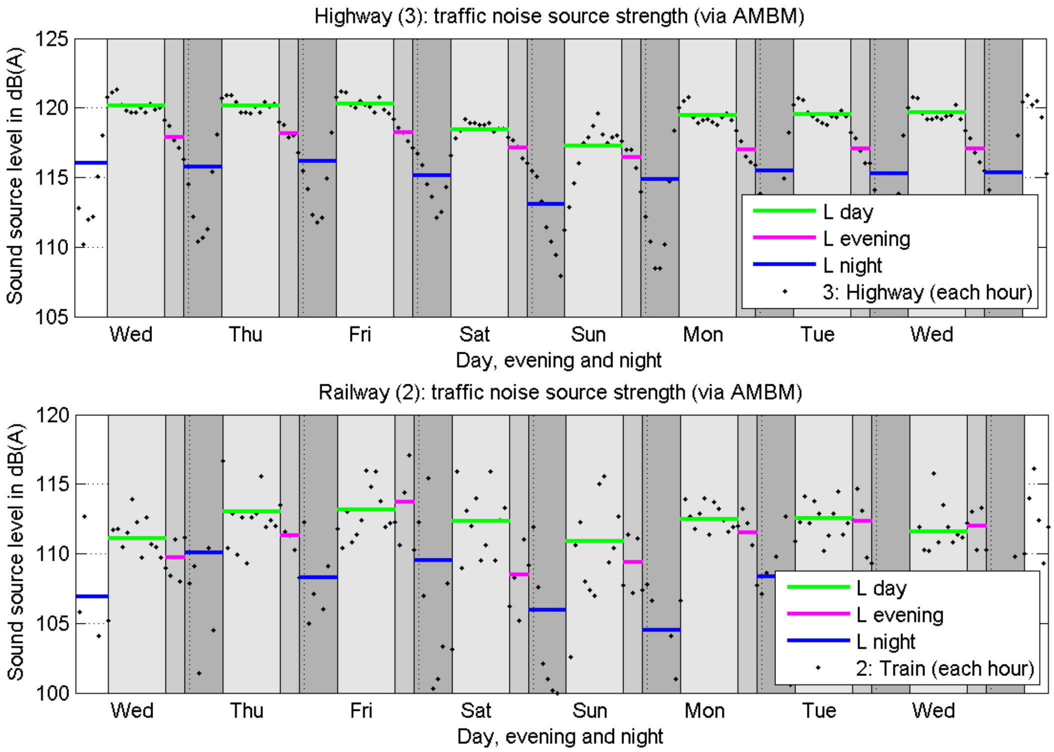

Figure 5. Top: Highway source level (3) (i.e. a line-source) as a function of time in dB(A) determined via microphone measurements and acoustic engineering model. Bottom: idem for railway source (2).

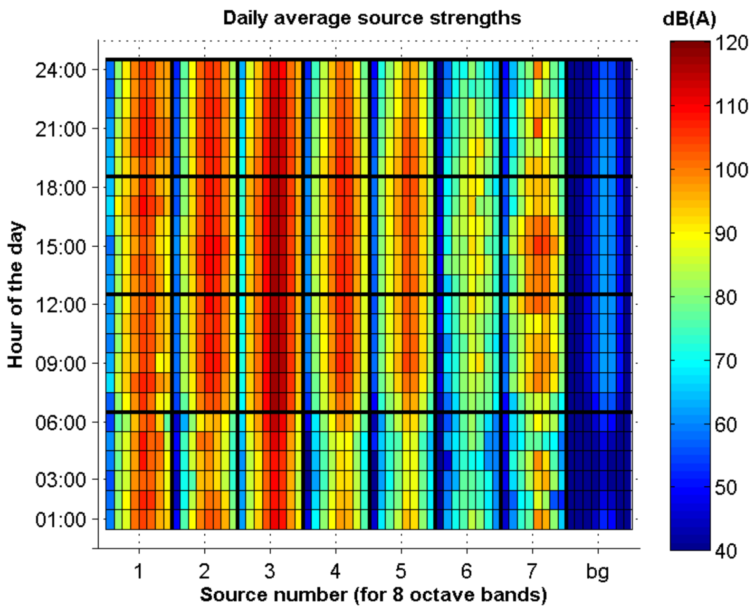

Figure 6. Daily averaged source levels for 7 sources and background level, for 8 octave bands ranging from 63 to 8000 Hz. For source labels, see Figure 1.

As a first step a *forecast* for the mean and covariance of the state x_k is determined with equation (2). Next, with the data observations y_k available, an *analysis* step is done to get the new values for the mean and (likely smaller) covariance of state x_k:

$$\bar{x}_k^a = \bar{x}_k^f + \mathrm{K}_k(y_k - \mathrm{H}\cdot\bar{x}_k^f) \tag{4}$$

with matrix K the Kalman gain. It is a function of the uncertainties in x and y and ranges between 0 and 1. It is defined as the gain that provides the smallest uncertainty of the state vector x, i.e. the source levels.

3.3 Data assimilation results

In Figure 7 the results of the Kalman filtering for the source levels are shown: the top figure depicts the mean 1000 Hz octave band source levels for the highway, the bottom figure for the railway. In black the source level is based on the daily averaged source level only, in blue the data assimilated mean results are shown. For the standard deviations, values of 2,5 and 1 dB were assumed for the model and the measurements (also to include non-traffic noise), respectively. For the source levels the standard deviations were derived from the auto-regressive model and varied from 1 dB for the highway to 4 dB for the railways and roads.

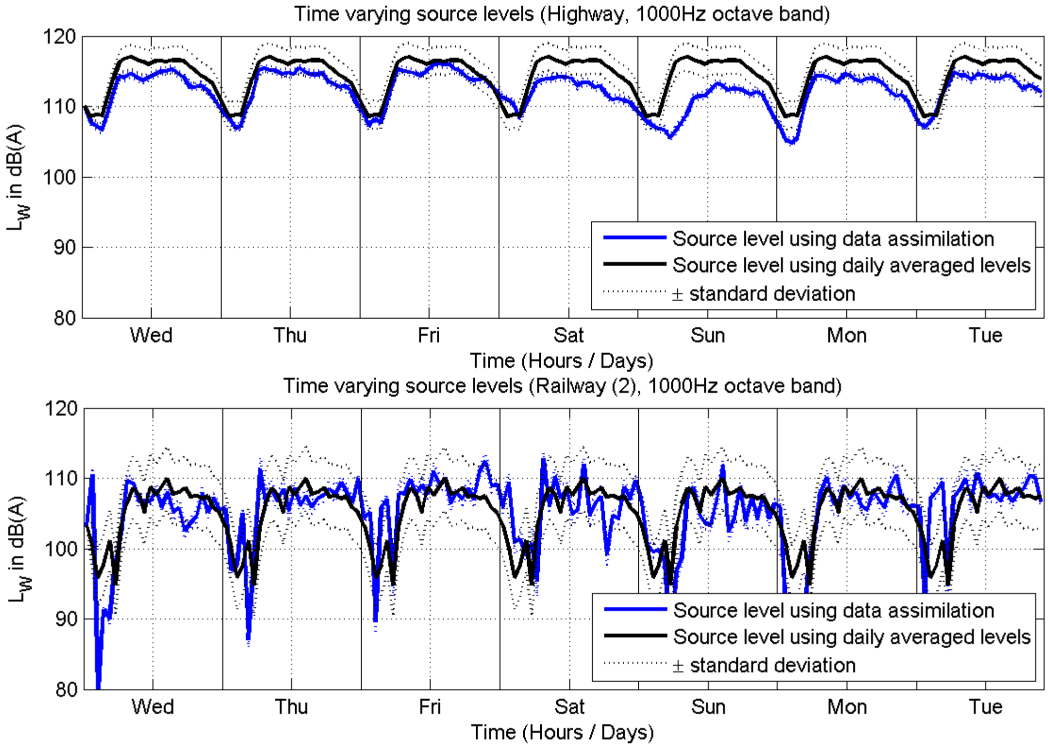

Figure 7. Source levels determination by using data assimilation of the hourly averaged measurements (in blue) and by using the daily averaged source levels (in black). Top: for Highway (source 3) and 1000 Hz octave band. Bottom: idem for Railway (source 2), see Figure 1.

The available uncertainties can be used to judge (or screen) if observations are realistic or not. For example, an observation can be rejected if it is too far from the range of likely values. Here, we assume that observations are rejected if it exceeds 3 times the standard deviation. Note that the screening procedure is valuable to check the results afterwards; if too many observations are rejected the uncertainties are unable to explain the difference between observations and simulations. The comparison may also show the need to change parameters in the acoustic engineering model; see also Figure 3 "Update model".

Figure 8 shows a comparison of simulated receiver results with observations for two locations: near the highway and near a railway. For the observations a standard deviation of 1 dB is shown with red error bars. A comparison for the highway shows that the simulated receiver level is about 1 to 2 dB higher than the observations (for basic node nr. 23), but these fall within one standard deviation. Also for other nodes the observations can be somewhat higher or lower than the simulations as the Kalman filter weights the errors of the complete system.

Similar results are shown near the railway. The more dynamic nature of these sound levels is well captured.

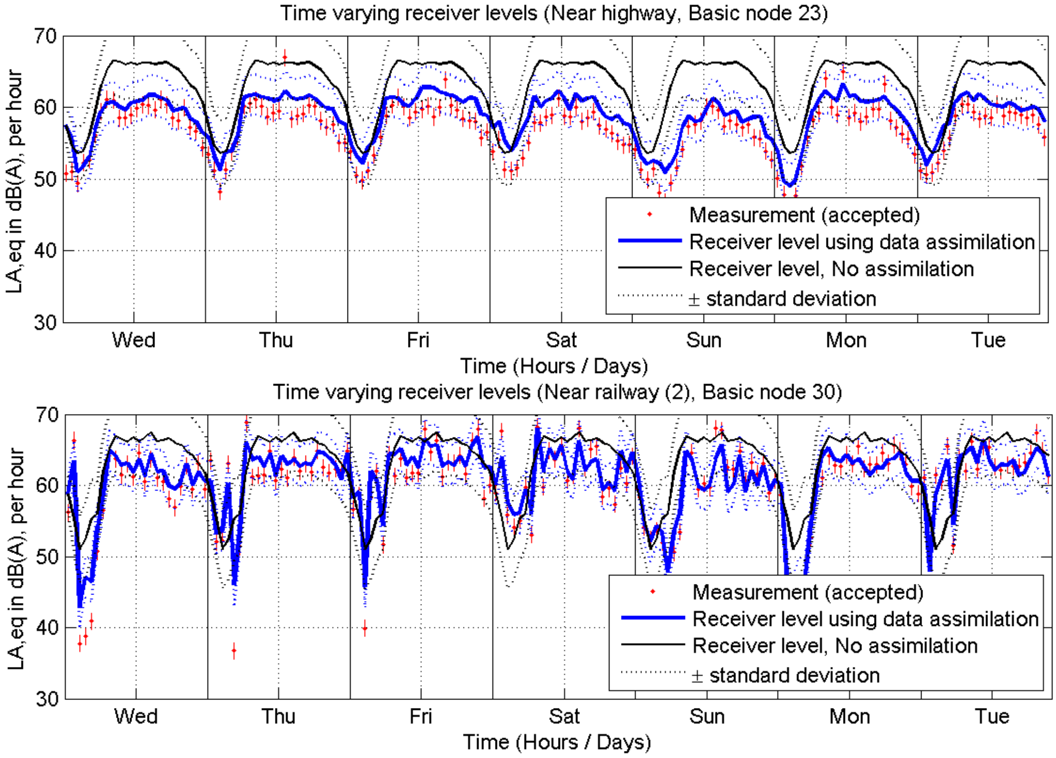

Figure 8. Calculated receiver levels near the highway (top, source 3) and near a railway (bottom, source 2) by using data assimilation of the hourly averaged measurements (in blue) and by using the daily averaged source levels (in black). In red the measurements with a 1 dB standard deviation. See also Figure 1.

4. ACOUSTIC MODEL BASED MONITORING RESULTS

4.1 Noise maps

A conventional noise map with L_{den} values is shown in Figure 9. Here, more than 7 traffic noise sources were used.

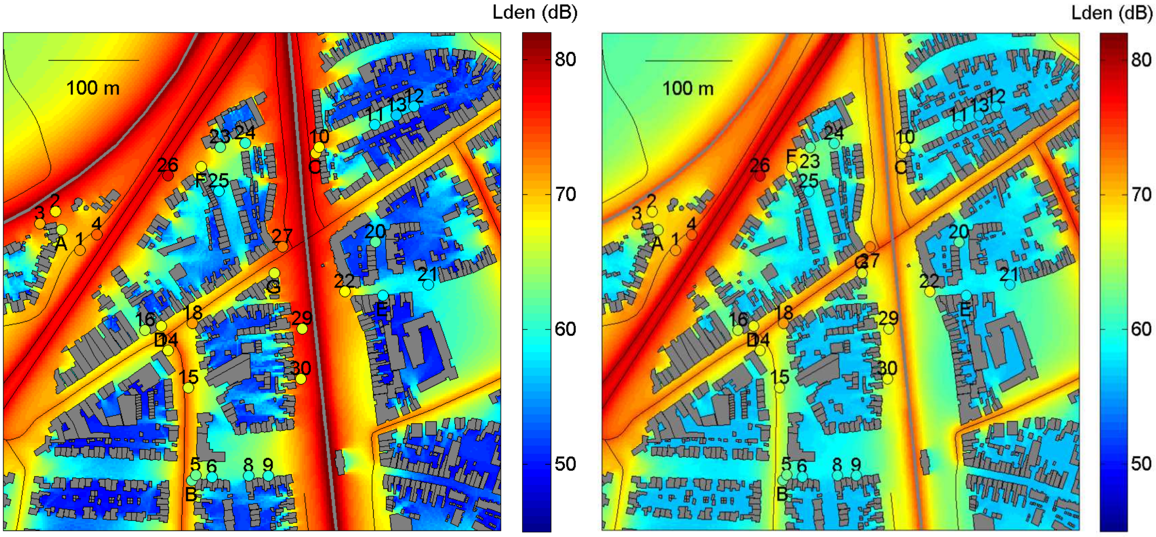

Figure 9. Left: Noise map showing L_{den} based on standard input for traffic data. The markers show the measured L_{den} values. Right: Similar, but with the traffic noise adapted to the measurements.

The left hand side depicts the L_{den} values for the urban area when using the standard traffic intensity database. Also, the 35 measured values are shown (based on 8 days). Differences of several dB's can be observed. Based on the measurements, it appeared that for the railway noise the source levels needed to be decreased while for the major local road the level needed to be increased.

The right hand side figure shows the newly calculated sound levels and a much better similarity with measurements. For these L_{den} levels this was done by manually tuning the source levels. Assuming that the measurements are representative for a year, these latter L_{den} values should be used for noise abatement studies and exposure-response relations.

The AMBM technique provides the noise map for different moments in time, using $L_{A,eq}$ values. For instance, it is possible to store the noise history and to create a noise movie. In Figure 10 three snapshots for the noise map are shown for a 5 minutes average sound level. In the early morning only the highway is the dominant source, while later in the morning all roads contribute to the sound level. The snapshot at 21:20 hours shows that for a short moment the railway can be the most dominant source.

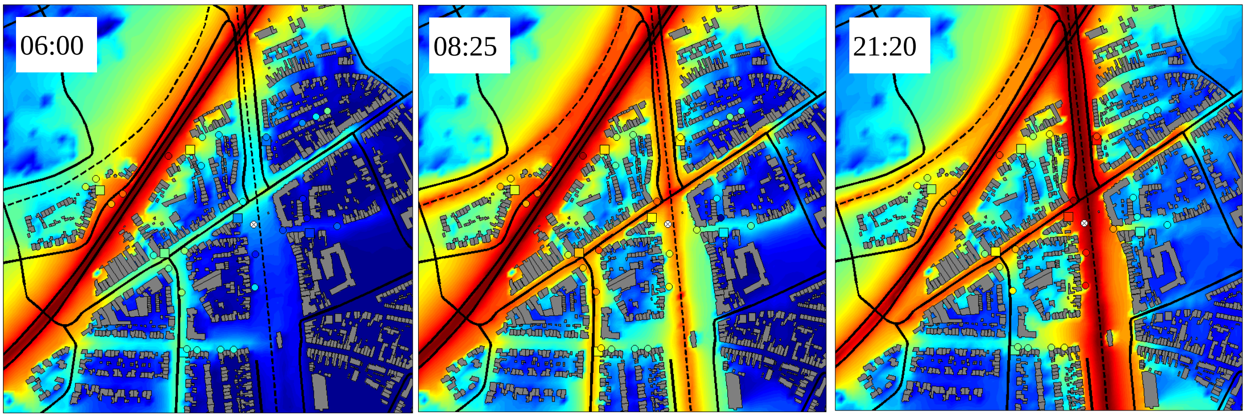

Figure 10. Snapshots at three different times from a dynamic noise map: $L_{A,eq}$ averaged over 5 minutes.

4.2 Noise dynamics

By using microphone measurements the varying sound levels are captured. However, measurements can only be performed at a limited number of locations. By using AMBM the noise dynamics can be calculated for the entire area. In Figure 11 the sound levels are shown for two locations (or addresses) were no measurements were carried out. The top figure shows the sound levels near the major road. It compares the L_{den} value to: the varying day / evening / night values, and selections of the $L_{A,eq(1\ hour)}$ and $L_{A,eq(60\ s)}$ values. The bottom figure is for a location near the major road and a railway and shows the separate contributions from rail and road. Here, the rail is the dominating source. Also, the difference between day and night levels is smaller than for the former address.

In practice it may be difficult to reduce an L_{den} value, but from the perspective of annoyance there may be opportunities to reduce the annoyance by altering the noise dynamics, i.e. the soundscape.

A second example is showing the noise dynamics in Figure 12. The L_{10} and L_{90} levels have been determined at 82 addresses in the urban area, using the $L_{A,eq(60\ s)}$. The difference L_{10}-L_{90} indicates the spread in sound levels; between relatively quiet moments (L_{90}) and more noisy moments (L_{10}). On the horizontal axis the L_{day} values at the addresses are given for the road and rail separately, while on the vertical axis the corresponding noise dynamics L_{10}-L_{90} values are shown. For the day period two clusters can be distinguished: one with low values for the noise dynamics and a limited dependency on the sound level, and one with much higher noise dynamics and increasing linearly with L_{day}. These two clusters are dominated by road and rail, respectively. Further work is foreseen to relate noise dynamics parameters to the local annoyance responses.

5. CONCLUSIONS

For urban areas with high traffic noise levels, an acoustic model based monitoring (AMBM) technique has been described to obtain accurate results for the entire area. This is achieved by combining measurements and model results. The AMBM technique has been illustrated for an urban area and the results have proven to be more accurate than a standard approach. These results can be

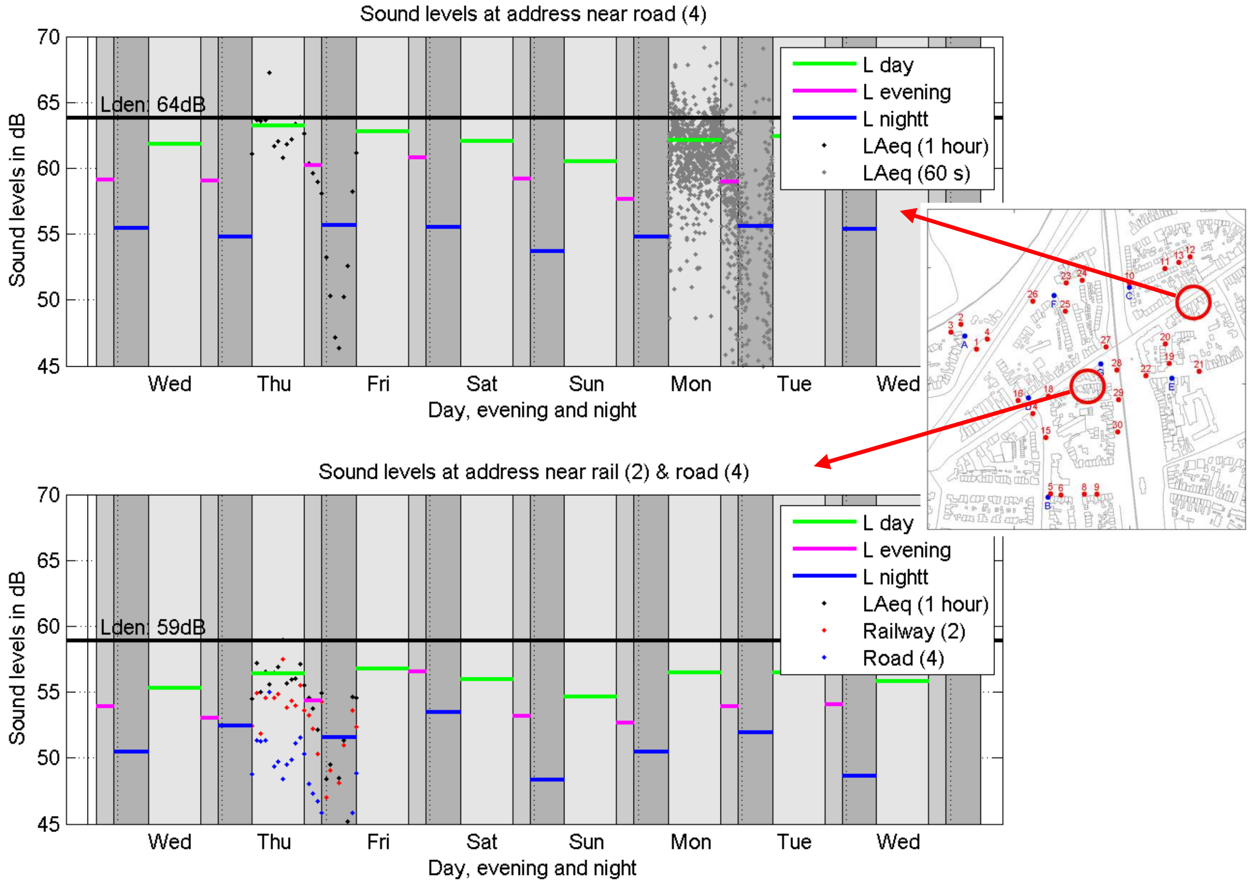

Figure 11.Calculated sound levels at two locations (see inset), based on local traffic noise measurements. Varying noise levels during the week are shown for day-evening-night periods. The markers show the variation of the sound levels ($L_{A,eq}$) per hour and per minute. In the bottom figure the contributions of rail and road traffic noise has been distinguished.

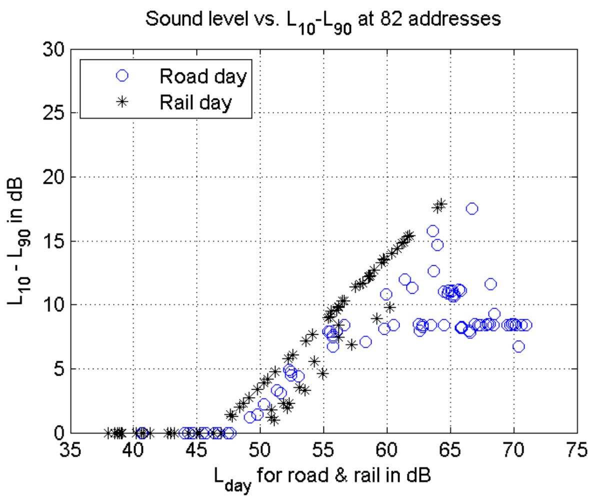

Figure 12. Calculated sound levels at 82 addresses in the urban district for road and rail noise versus the noise dynamics $L_{10} – L_{90}$ at the same address, using the measured traffic noise dynamics (per minute).

used further to calculate (possible) noise control measures. Also, the noise history and noise dynamics are captured, so controlling noise and reducing noise annoyance may also address the soundscape of the area.

Data assimilation of the measurements into the acoustic engineering model has been described by using a Kalman filter. This filter combines simulations and observations while taking into account uncertainties in both. With the data assimilation approach the time-varying traffic noise source levels were determined and a good correspondence of the simulated receiver levels and measurements was found.

ACKNOWLEDGEMENTS

The municipality of Vught, The Netherlands, is acknowledged for their assistance to this project.

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