Experimental study of traffic noise and human response in an urban area: deviations from standard annoyance predictions

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ABSTRACT

Annoyance and sleep disturbance by road and rail traffic noise in an urban area are investigated. Noise levels Lden and Lnight are determined with an engineering noise model that is optimized for the local situation, based on local noise measurements. The noise levels are combined with responses of 71 inhabitants to an annoyance survey to derive local exposure-response relations, using the regression method with censored normal distributions developed by Miedema and coworkers. It is found that the local exposure-response relations deviate considerably from the 'standard' relations derived from international annoyance surveys. Noise events reported by the inhabitants – such as freight trains passing through the area at night – are described to illustrate the local situation. Future scenarios for the urban area are also analyzed, including measures aimed at reducing road and rail traffic noise. Numbers of highly-annoyed inhabitants in the urban area are calculated for different scenarios by applying the local exposure-response relations to the total population in the area of about 1000 inhabitants.

Keywords: traffic noise, human response, measurements
I-INCE Classification of Subjects Numbers: 52.3, 52.4, 63.2, 68.3, 76.1

1. INTRODUCTION

Traffic noise is a major environmental problem in many urban areas, and causes annoyance and sleep disturbance of the inhabitants (1,2). In the EU, the standard approach for analyzing a traffic noise problem in an urban area is based on calculations with simple models (3). First noise levels in the area are calculated with an engineering noise model and next empirical exposure-response relations are applied to estimate the prevalence of annoyance and sleep disturbance. The focus is often on annoyance at home, and therefore the noise levels are calculated at the facades of dwellings.

A limitation of the standard approach is that the results represent average situations. The noise levels correspond to average noise emission and transmission (4,5,6). The exposure-response relations represent averages over a large set of noise annoyance surveys (1,2,7,8). Consequently, considerable deviations may occur from standard annoyance predictions in specific situations. Standard predictions should be considered as crude estimates, and more accurate results can be obtained only by more detailed and local investigations.

In this article we present such a detailed local investigation of a traffic noise problem in an urban area. An experimental study was performed in an area with about 1000 inhabitants, who are exposed to road and rail traffic noise. Noise levels in the area were measured at 33 locations during one week. Simultaneously, annoyance and sleep disturbance in the area were monitored by means of surveys, both surveys of long-term annoyance and sleep disturbance and surveys of annoyance and sleep disturbance on specific days of the week of the measurements.

An objective of this work was to assess the deviations from standard predictions in this specific situation. A more general objective was to develop a methodology for local assessment of a traffic noise problem. The methodology consists of the steps indicated in Fig. 1.

- The first step is the determination of traffic noise levels in the area, based on a combination of

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sound measurements and an engineering noise model. The model is ‘calibrated’, or optimized, by adjusting model parameters based on measured local noise levels.
- The second step is the determination of local exposure-response relations for annoyance (or sleep disturbance), based on the results of a local noise annoyance survey among a limited number of inhabitants in the area.
- The third step is a traffic-noise impact assessment: the calibrated noise model (step 1) and the local exposure-response relation (step 2) are applied to all inhabitants in the area, which results in an estimate of the overall prevalence of annoyance in the area.
- An optional fourth step is a scenario study, in which the impact assessment is repeated for a scenario, for example a scenario with a noise reduction measure.

For comparison, the standard approach for analyzing traffic noise employs a standard noise model in step 1 and a standard exposure-response relation in step 2.

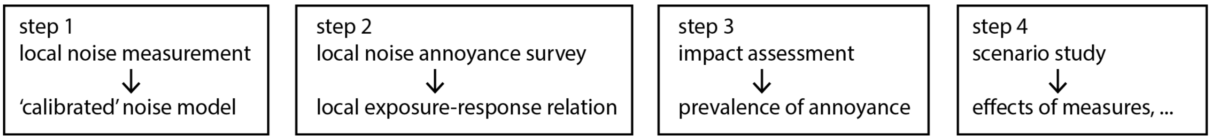

Figure 1 – Illustration of steps of the local impact assessment methodology employed in this study.

2. SETUP OF THE EXPERIMENTAL STUDY

Figure 2 shows a map of the urban area investigated in this work. The area is located in the city of Vught in the Netherlands. Two busy railway lines and one major road (road N65) are major sources of traffic noise. The flow on road N65 is around 50 000 vehicles per 24h. In addition there are several minor roads in the area. In collaboration with the authorities of Vught, 463 dwellings in the area were selected. The inhabitants of the dwellings were addressed by mail, with a request to participate to one or more of the following three elements of a local scientific study of traffic noise.

a) A single questionnaire with questions about long-term traffic noise annoyance and sleep disturbance, and other characteristics that may be related to the annoyance.
b) A daily questionnaire with questions about traffic noise annoyance and sleep disturbance during the actual day or night.
c) Noise measurements with microphones at various locations in the area, including locations near dwellings (in the garden for example).

In total 82 inhabitants agreed to participate.

The questionnaire of element a) was filled in by 71 participants. It consisted of 34 questions about the dwelling of the participant, traffic noise annoyance, sleep disturbance, vibrations caused by traffic, expectations about future developments of traffic in the area, and personal characteristics. The questions about annoyance and sleep disturbance were formulated with an 11-point annoyance scale running from zero (not at all annoyed) to 10 (extremely annoyed), referring to the situation at home during the past 12 months, distinguishing different traffic sources.

Elements b) and c) were executed simultaneously during one week at the end of September 2013. The daily questionnaire of element b) was filled in by 35 participants. It consisted of two questions about daily annoyance (day and evening) and one question about sleep disturbance, again with an 11-point scale. In addition, inhabitants were asked to describe specific noise events, including the time of the event and the activity of the inhabitant at that moment.

The noise measurements of element c) were performed at 33 locations. The locations were carefully selected based on a standard noise map of the area calculated according to the Dutch standard calculation model for traffic noise (4), which is presented in Sec. 3. Sound levels were recorded continuously during one week. Most microphones recorded broadband sound levels (4 per second) and some microphones also recorded sound spectra (8 per second). The microphones were mounted on tripods or lampposts, at a height of 3 m. Figure 3 shows an example of the sound signal recorded by the microphone labeled ‘a’ in Fig. 2, near railway line 2. Peaks exceeding 80 dB correspond to train passages. During the night sound levels are lower than during the day.

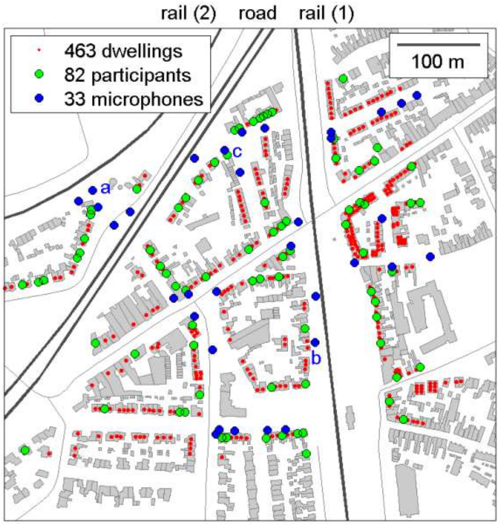

Figure 2 – Map of the urban area investigated in this work. Black lines represent two railway lines (labeled 1 and 2) and one major road (double line, road N65), grey lines represent minor roads, and grey polygons represent buildings. Also indicated are 463 selected dwellings (red), 82 dwellings of participants (green), and 33 microphones used for the noise measurements (blue).

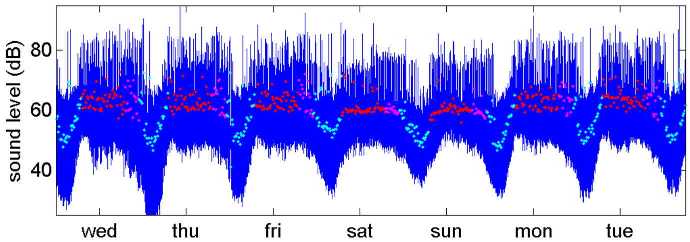

Figure 3 – Example of a sound signal, recorded at the microphone labeled 'a' in Fig. 2, near railway line 2, during one week starting at time 0:00 on Wednesday. Dots are average levels over successive periods of 15 minutes, with different colors for the day (red), evening (purple), and night (cyan).

3. MEASURED AND CALCULATED SOUND LEVELS

Figure 4 shows the standard L_{den} noise map of the area, i.e. the L_{den} noise map calculated with the Dutch standard calculation model for traffic noise. Figure 5 shows the corresponding standard L_{n} noise map. Levels L_{den} and L_{n} are the day-evening-night level and the night level, respectively (3). The night level is denoted as L_{night} in Ref. 3, but here we use the shorter notation L_{n}. Road and rail traffic noise levels were summed logarithmically for Figs. 4 and 5. The two railway lines and the road N65 are clearly visible as bands of high noise level on the map. The measured L_{den} and L_{n} noise levels at the 33 microphone positions – averaged over the measurement week - are shown as colored dots. Deviations are observed in particular near the railway lines: here the measured levels are considerably lower than the calculated levels. Similar deviations between measurement and calculation were observed for passages of individual trains. Apparently the noise emission of trains in this area is lower than according to the Dutch standard model. This may be due to quiet trains and / or quiet tracks in this area.

Figures 6 and 7 show the 'calibrated' L_{den} and L_{n} noise maps, showing good agreement with the measured noise levels. The calibration was performed as follows. Six sources of traffic noise were distinguished: two railway lines, major road N65, two minor roads, and the combination of all other minor roads. Each source was assigned an adjustable level correction. In addition a background level was included to represent all other noise sources, both traffic on small roads not included in the road network and other sources. By optimization we found the values of the six level corrections and the background level. Separate optimizations were performed for the day period, evening period, and night period. As expected, we found negative level corrections for the two railway sources, in the range -6 dB to -11 dB. The corrections for the road N65 and the other roads were closer to zero. The optimized background level was 55, 52, and 44 dB for the day, evening, and night, respectively.

Differences between levels calculated with the calibrated noise model and measured levels are of the order of 1 dB. The average absolute difference is 1.4 dB for L_{den} and 1.2 dB for L_{n}. The largest differences occurred for three microphones during the day, which was caused by the fact that construction noise occurred near these microphones during the day. For the analysis of annoyance and sleep disturbance, described in the next section, we employed the calibrated noise model. The above mentioned background levels were included in the model as road traffic noise contributions, neglecting the fact that part of the background levels are due to non-traffic sources. As a check, the analysis described in Secs. 4 and 5 was repeated excluding the background levels: this gave slightly different exposure-response relations, but the effect on the impact assessment (percentages of annoyed and sleep-disturbed inhabitants) was negligible.

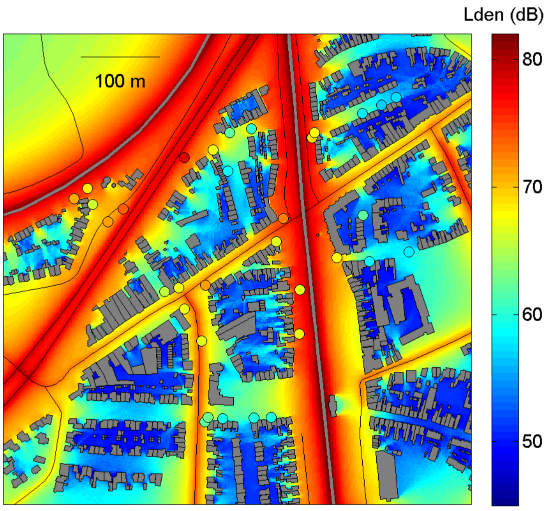

Figure 4 – Standard L_{den} noise map. The measured L_{den} noise levels at the 33 microphone positions are shown as colored dots.

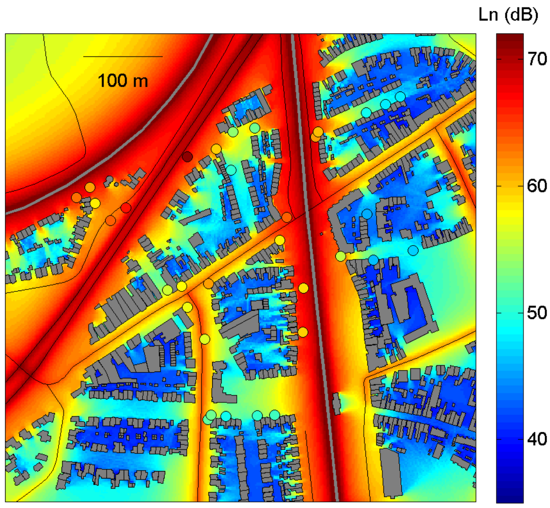

Figure 5 – Standard L_{n} noise map. The measured L_{n} noise levels at the 33 microphone positions are shown as colored dots.

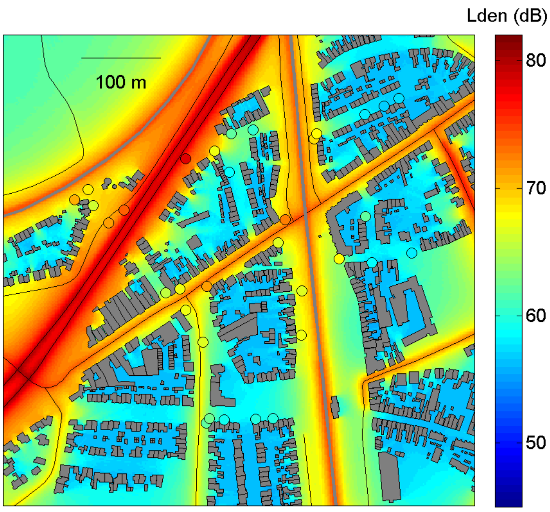

Figure 6 – ‘Calibrated’ L_{den} noise map.

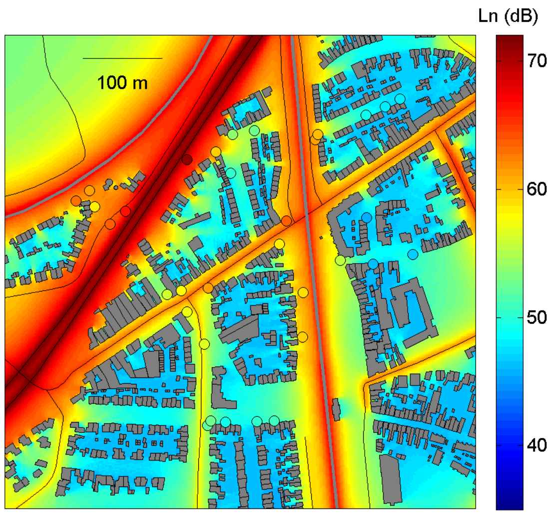

Figure 7 – ‘Calibrated’ L_{n} noise map.

4. ANNOYANCE AND SLEEP DISTURBANCE

4.1 Exposure-response relations and impact assessment

Local exposure-response relations were derived by combining the long-term annoyance and sleep-disturbance scores (element a, see Sec. 2) with L_{den} and L_{n} noise levels calculated with the calibrated noise model described in the previous section.

Figures 8 and 9 show graphs of the annoyance score A for road and rail traffic noise as a function of the L_{den} level, denoted as $A(L_{den})$. The graphs show the individual scores (dots), linear and nonlinear regression lines (blue lines), and the standard curve (grey line). The linear regression yielded correlation coefficients of 0.41 and 0.58, respectively, and p-values less than 0.001. The nonlinear regression was performed according to the method developed by Miedema and Oudshoorn (7). The standard curves in the figures are the corresponding nonlinear regressions to a large set of noise annoyance surveys (7). The local exposure-response relations give considerably higher annoyance scores than the standard curves do.

Figures 10 and 11 are similar to Figs. 8 and 9, but now for sleep disturbance. The exposure-response relations are denoted as $S(L_n)$. The correlation coefficients are 0.38 and 0.46, respectively, and the p-values are less than 0.001.

We briefly describe the nonlinear regression method (7). The individual annoyance score is denoted as A^* in Ref. 7 and is renormalized to a scale from 0 to 100. It is assumed that A^* corresponds to a (latent) random variable A running from $-\infty$ to $+\infty$ according to the linear expression $\beta_0 + \beta_1 L_{den} + u$, with coefficients β_0 and β_1 and random component u, such that $A^* = A$ for $0 \leq A \leq 100$. A normal distribution is assumed for u and A, corresponding to a censored normal distribution for A^*. The nonlinear regressions in Figs. 8 and 9 represent the expectation value of A^* as a function of L_{den}. For β_0 and β_1 we used the values from the linear regression, and for variance σ^2 of u we used the value of 1000 (based on values in Refs. 7 and 8), where we note that results of this study are not very sensitive to the precise value of σ^2. For the standard curves we used values for β_0, β_1, and σ^2 from Refs. 7 and 8.

Using the nonlinear regression lines shown in Figs. 8 and 9, we have derived corresponding relations for the percentage of inhabitants that is highly annoyed, indicated as P_{HA}. A person is called highly annoyed if the annoyance score is 72 or higher on a scale from 0 to 100. The curves $P_{HA}(L_{den})$ are shown in Figs. 12 and 13, together with the corresponding standard curves. Figures 14 and 15 show $P_{HSD}(L_n)$, i.e. the percentage highly sleep-disturbed persons as a function of L_n.

Next we have performed an impact assessment. Noise levels L_{den} and L_n were calculated for all 463 dwellings in the area (see Sec. 2). We assume 2.2 persons per dwelling, so we have approximately 1000 inhabitants. The exposure-response relations from Figs. 12-15 were used to calculate the distributions shown in Figs. 16-19. The blue bars represent the exposure distribution (P_E, percentage exposed), while the red bars represent the annoyance/sleep disturbance distribution (P_{HA}/P_{HSD}). We see for example that in total 34% of the 1000 inhabitants is highly annoyed by road traffic noise.

The percentages are collected in Table 1 (‘present situation’). For comparison, also the percentages according to a standard prediction are given, which are much lower. Here standard prediction means that standard noise levels are used (calculated without local model ‘calibration’) and the standard exposure-response relations are used.

An important question is *why* annoyance and sleep disturbance is so much higher than according to the standard prediction. We have tried to find answers to this question by performing a statistical analysis of all responses of the participants in the questionnaires. A detailed discussion of this analysis will be presented elsewhere, but here we give a few conclusions drawn from the analysis. For road traffic noise annoyance it was found that: i) both the major road N65 and the minor roads play a role, ii) noise peaks and vibrations play a role, and iii) annoyance occurs in particular during sleep/rest and during interaction with TV/radio/computer. For rail traffic noise annoyance it was found that: i) high tones and vibrations play a role, and ii) annoyance occurs in particular during conversation. Further, it was found that accumulation of road and rail traffic noise does not explain the high annoyance scores. For example, the statistical prediction of railway traffic noise annoyance as a function of railway noise exposure was not improved by including road traffic noise exposure as an additional variable.

4.2 Daily questionnaires

The annoyance and sleep-disturbance scores from the daily questionnaires (element b, see Sec. 2) were found to be considerably lower than the long-term scores (element a), on the average. The daily scores averaged over the seven days of the measurement week are shown in Figs. 20-23, together with linear regression lines. It is not clear why the week average scores are so much lower than the long-term scores (i.e. the scores representing the past 12 months). The difference cannot be attributed to much lower traffic noise levels during the week. The measurement took place after the annual summer holiday, so there was no holiday traffic ‘dip’. Construction noise at one location during the day may have affected the annoyance scores of nearby participants. We found that annoyance during the weekend was not significantly higher or lower than during the week.

As indicated in Sec. 2, participants could describe specific annoying noise events on the daily questionnaires. Some participants did this very carefully, even during the night. Other participants described noise events more in general, without exact reference to times of events. Here we present a few examples.

Figure 24 shows the four noise events that a participant near microphone ‘b’ (see Fig. 2) noted on one day. The dwelling of the participant is close to railway line 1. The upper graph shows the signal at the microphone during the day, with the moments of the events noted by the participant indicated in red. The two lower graphs show zoomed-in sections of 20 minutes centered at events 1 and 4. Event 1 is the passage of a freight train at 3:42h in the night. Event 4 is the passage of an intercity train at 18:15h. The peaks in the sound signal agree well with the times noted by the participant. The participant also noted to sleep preferably with slightly open window, but sometimes the window is closed because of the noise.

Figure 25 shows the three noise ‘events’ that a participant near microphone ‘c’ (see Fig. 2) noted on one day. The dwelling of the participant is close to major road N65. Actually this participant did not note specific events, but rather a pattern of noise events, which was noted identically for every day of the week. Traffic on the N65, in particular trucks, disturbed sleeping in the early morning (5h-7h), around dinner time (16h-18h), and late in the evening (around 23h). These three periods are marked in red above the upper graph in Fig. 25, showing the signal at microphone ‘c’ during the day. The participant noted that noise peaks and vibrations contributed to the annoyance. During the day, the regular noise level variations due to the repetition of traffic stopping and pulling up at the traffic light on the N65 (located in the lower left corner on the map in Fig. 2) was also mentioned as an annoying element of the noise. The regular variations are visible in the middle graph in Fig. 25, which is a zoomed-in section of two hours (16h-18h). A Fourier analysis of the fluctuating sound level reveals that the time period of the traffic light is 2 minutes (124 sec), as shown by the peak in the Fourier spectrum in the lower graph in Fig. 25. De quantity shown is the 10-base logarithm of the spectral density of the sound pressure amplitude $10^{L/20}$, where L is the A-weighted sound level. This type of sub-Hertz spectra have been related to the human appreciation of the urban soundscape (9).

Figure 26 shows a further analysis of the effect of the traffic light on the noise level at microphone ‘c’. The upper graph shows the sound level averaged (logarithmically) over successive periods of 2 hours, for the seven days of the measurement week. The sound level peaks at 8h and 17h, except in the weekend when the levels are a bit lower. The middle graph shows the value of the log spectral density at time interval 124 s (i.e. the peak value in the lower graph in Fig. 25), which also reaches the highest values at 8h and 17h. At these times the cars seem to drive more or less ‘bumper to bumper’, and there is no room for variations in the flow except by the regular interruption by the traffic light.

The lower graph in Fig. 26 shows the number of acoustic events per 5 min. An acoustic event is defined as a moment when the sound level is at least 3 dB above the level $L_{50,5\text{min}}$ (50% exceedance level based on 5 minute intervals) during at least 3 seconds. We see that the number of events per 5 min shows a maximum not at 8h and 17h but rather 2h before the peak at 8h, i.e. around 6h. Apparently, around 6h there is more room for variations of the flow and the noise level, while at 8h the ‘bumper to bumper’ driving suppresses the variations.

5. SIMPLE SCENARIO STUDIES

To get insight into the possibilities of reducing the annoyance and sleep disturbance in the area, we have performed a few simple scenario studies. This means that we have repeated the impact assessment described in Sec. 4.1 for situations where the noise levels in the area have been modified.

We have considered the following four scenarios.

A. An increase of the number of trains on both railway lines by a factor of five.
B. A decrease by 10 dB of the noise levels from railway line 1.
C. A decrease by 10 dB of the noise levels from major road N65.
D. A decrease by 10 dB of the noise levels from all roads.

The noise level reductions may be achieved by noise barriers, or by development of a (rail)road below ground level. The increase of the number of trains under A may seem large, but a factor of five is one of the things that are being considered for this area.

The results of the scenario studies are given in Table 1. Scenario A yields an increase of P_{HA} and P_{HSD} by about 45%, and scenario B yields a decrease by about 40%. The effect of scenario C is rater small, due to the fact that road traffic noise annoyance is caused not only by major road N65 but also by the other roads in the area. The effect of scenario D is larger, but it should be noted that it is not easy to achieve a noise reduction of 10 dB for all roads in the area. Consequently, it appears that noise reduction measures on the railway lines are most feasible and effective.

6. CONCLUSIONS

Based on an experimental study of traffic noise and human response in an urban area, a methodology for local impact assessment of traffic noise has been presented. Accurate local traffic noise levels and exposure-response relations were determined by combining engineering noise model calculations, locally measured noise levels, and annoyance and sleep-disturbance scores of inhabitants. It was found that percentages of highly annoyed and highly sleep-disturbed inhabitants are much higher in this area than according to standard predictions.

Table 1 – Percentages of inhabitants that are highly annoyed (P_{HA}) and highly sleep-disturbed (P_{HSD}), for the present situation (standard and optimized calculations) and for four scenarios.

	P_{HA}		P_{HSD}	
scenario	road	rail	road	rail
present situation (standard prediction)	12.7	7.3	6.6	3.6
present situation	34.2	34.6	25.1	25.0
A (rail 1,2 + 7dB)	34.2	**49.4**	25.1	**36.9**
B (rail 1 -10 dB)	34.2	**21.7**	25.1	**15.5**
C (road N65 -10 dB)	**31.6**	34.6	**22.2**	25.0
D (all roads -10 dB)	**22.5**	34.6	**14.8**	25.0

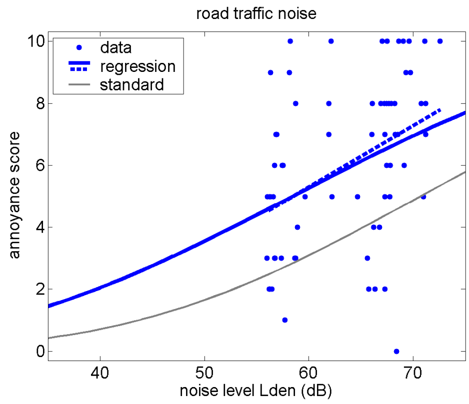

Figure 8 – Score $A(L_{den})$ for road traffic.

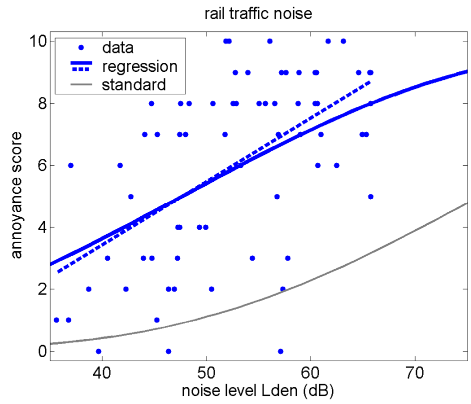

Figure 9 – Score $A(L_{den})$ for rail traffic.

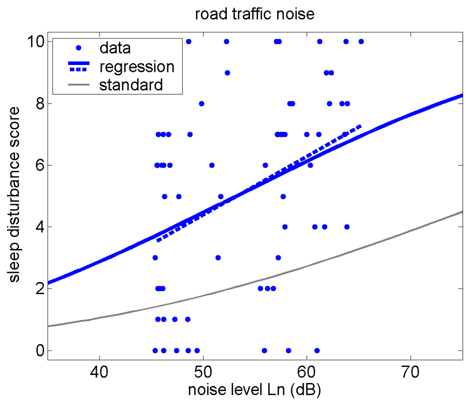

Figure 10 – Score $S(L_n)$ for road traffic.

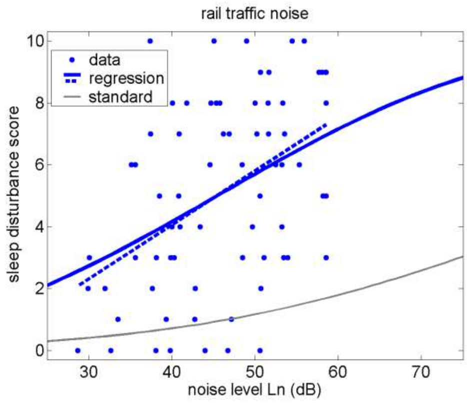

Figure 11 – Score $S(L_n)$ for rail traffic.

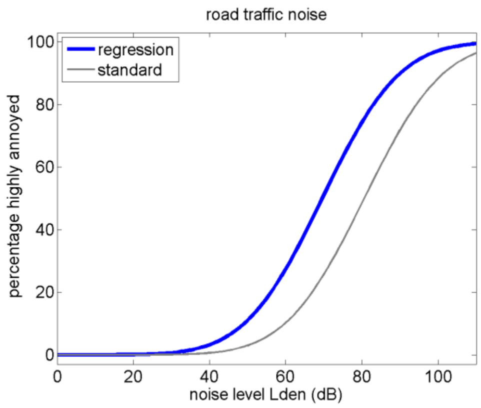

Figure 12 – $P_{HA}(L_{den})$ for road traffic.

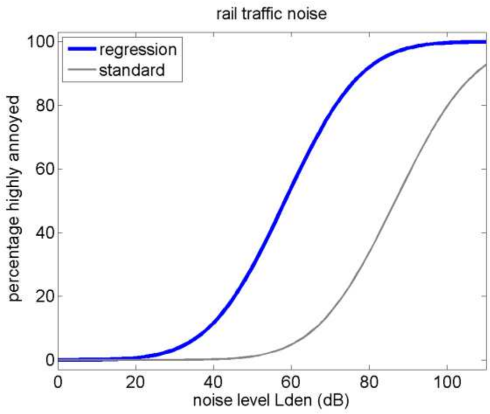

Figure 13 – $P_{HA}(L_{den})$ for rail traffic.

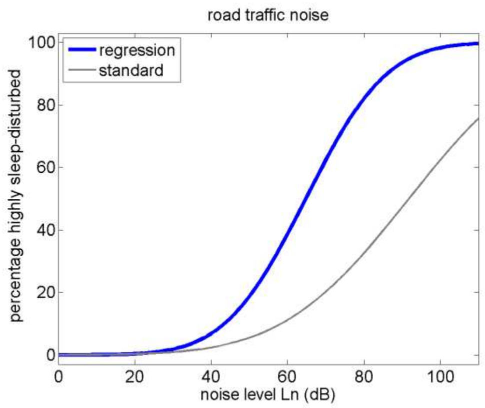

Figure 14 – $P_{HSD}(L_{n})$ for road traffic.

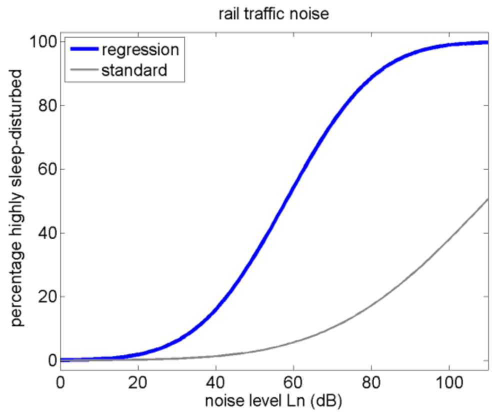

Figure 15 – $P_{HSD}(L_{n})$ for rail traffic.

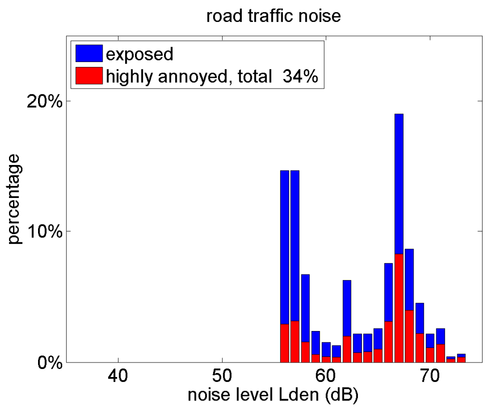

Figure 16 – $P_{E}(L_{den})$, $P_{HA}(L_{den})$ for road traffic.

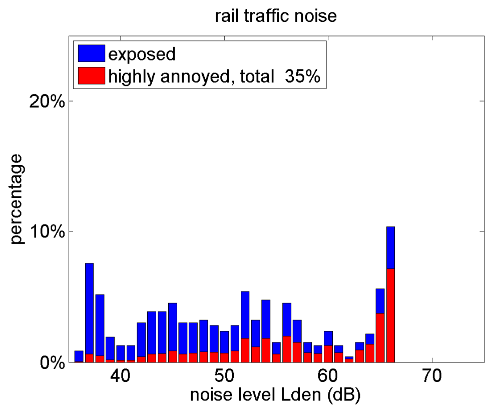

Figure 17 – $P_{E}(L_{den})$, $P_{HA}(L_{den})$ for rail traffic.

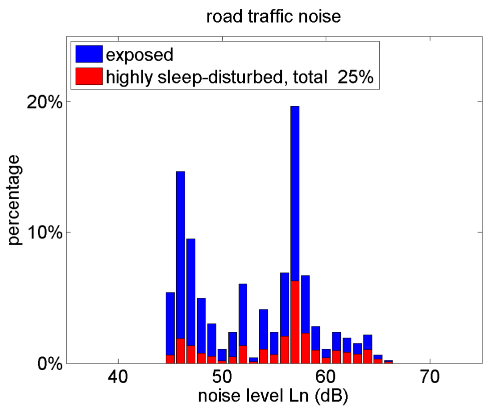

Figure 18 – $P_{E}(L_{n})$, $P_{HSD}(L_{n})$ for road traffic.

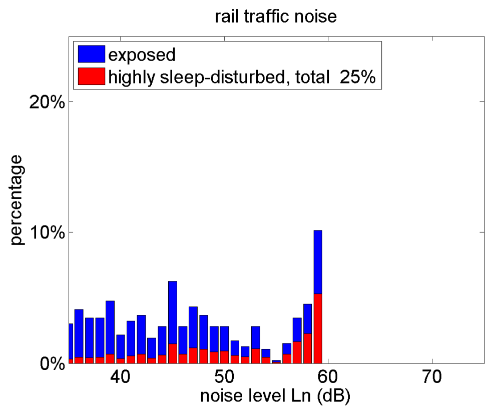

Figure 19 – $P_{E}(L_{n})$, $P_{HSD}(L_{n})$ for rail traffic.

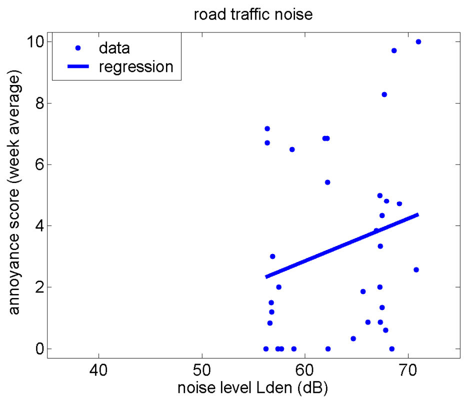

Figure 20 – Score $A(L_{den})$ for road traffic (week).

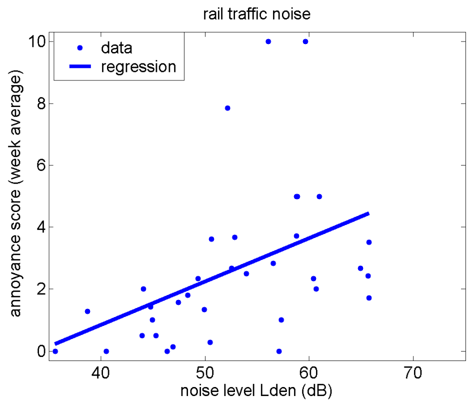

Figure 21 – Score $A(L_{den})$ for rail traffic (week).

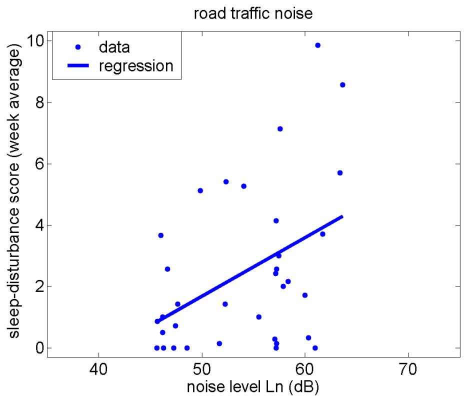

Figure 22 – Score $S(L_n)$ for road traffic (week).

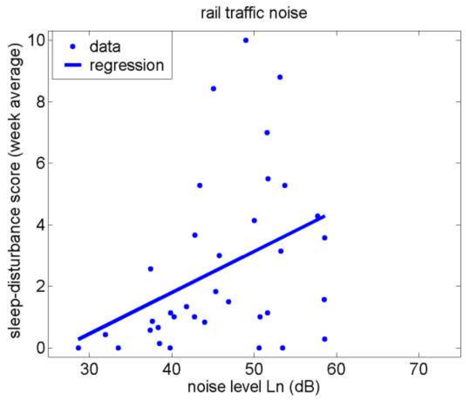

Figure 23 – Score $S(L_n)$ for rail traffic (week).

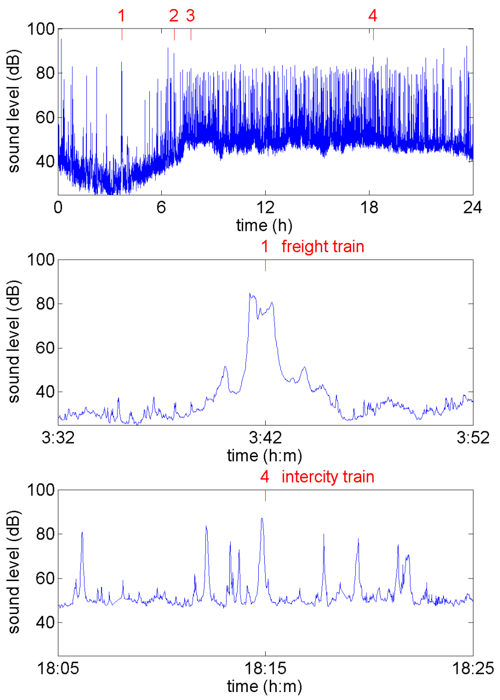

Figure 24 – Annoying noise events 1-4 noted by a participant near microphone ‘b’.

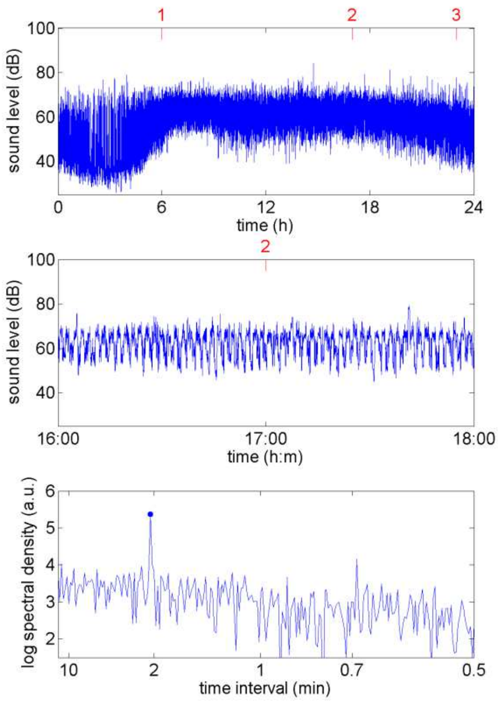

Figure 25 – Annoying noise events 1-3 noted by a participant near microphone ‘c’.

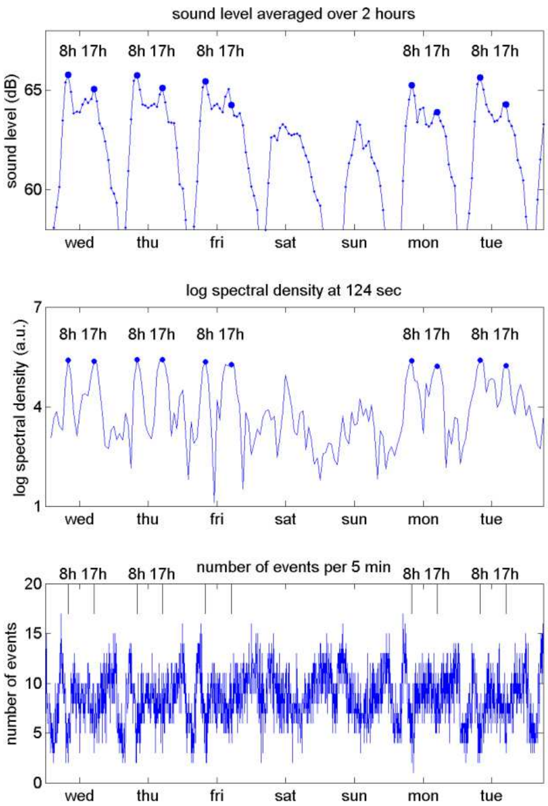

Figure 26 – Graphs of the sound level, log spectral density, and events at microphone ‘c’.

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