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Rating environmental noise on the basis of noise maps

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0 EXECUTIVE SUMMARY

The objective of QCity is to propose a range of measures and solutions with respect to noise in cities that can be integrated in the action plans that these cities (agglomerations) have to produce as a consequence of the EU Environmental Noise Directive (END). Noise maps can be the starting point for the design of measures that improve the noise climate. In order to evaluate the need for noise measures as well as the improvement that can be obtained with various measures, there is a need for a system that rates environmental noise on the basis of noise maps. The objective of this report is to present such a rating system.

The rating system needs to be evidence-based, so that it may be expected that effects in the community reduce if the system indicates that the rating improves. Therefore, in principal it needs to be based on empirical exposure-response relationships. A desk study has been carried out that uses the relevant empirical evidence on such relationships.

After its description, the rating system is presented as a stepwise procedure that can be read as a cookbook. Application of this procedure gives the following ratings of the environmental noise:

- **Overall noise climate in residential areas**: percentage highly annoyed (*%HA*);
- **Night-time noise climate in residential areas**: percentage highly sleep disturbed (*%HSD*);
- **Hot spots in residential areas**: (weighted) number of individuals above limit value L (n_L);
- **Non-Quiet area**: percentage area with L_{den} > 50 dB(A) ($AREA_{50}$).

These four indicators together constitute the proposed system for rating environmental noise on the basis of noise maps. The indicators can be calculated for a city or parts of it (neighbourhoods), for different types of sources (aircraft, road traffic, railways) separately or for the combined noise from these sources, and for the present situation as well as for noise maps of possible future situations based on scenario's.

The structure of the rating system appears to be solid and consistent with requirements formulated but it needs to be elaborated in some respects, and not all numerical values used could be equally founded on empirical evidence so that additional empirical research is needed. However, it is sufficiently developed to implement it in noise mapping software. After this has been done, its usage will be explored in practice. It is the first coherent proposal of a rating system that gives insight not only in the impact of L_{den} or L_{night}, but additionally in the influence of sound insulation, quiet side of a dwelling, and ambient noise in the neighbourhood, and, furthermore, that is not only applicable to noise from a single source, but also to combined noise from various sources.

1 INTRODUCTION

June 2002 the European Parliament and Council adopted the Environmental Noise Directive (END) (EC, 2002). END intends to provide a common basis for tackling the noise problem across the EU. It has the following four main objectives:

- Monitoring the environmental problem by requiring competent authorities in Member States to draw up "strategic noise maps" for major roads, railways, airports, and agglomerations. These maps will be used to assess the number of people annoyed and sleep-disturbed respectively throughout Europe.
- Informing and consulting the public about noise exposure, its effects, and the measures considered to address noise, in line with the principles of the Aarhus Convention
- Addressing local noise issues by requiring competent authorities to draw up action plans to reduce noise where necessary and maintain environmental noise quality where it is good.
- Developing a long term EU strategy, which includes objectives to reduce the number of people affected by noise in the longer term, and provides a framework for developing existing Community policy on noise reduction from source.

To meet these general objectives a number of actions are taken and projects started on national and EU level, including, as part of the EU Sixth Framework Programme, the project Quiet City Transport (QCity). The objective of QCity is to propose a range of measures and solutions with respect to noise in cities that can realistically be integrated both from an economic as well as from practical point of view in the action plans that these cities (agglomerations) have to produce as a consequence of END. Noise maps are the starting point for the design of measures that improve the noise climate. In order to evaluate the need for noise measures as well as the improvement that can be obtained with various measures, there is a need for a system that rates environmental noise on the basis of noise maps. This report presents such a rating system. The rating system has been developed taking into account the following conditions:

- The rating system needs to be evidence-based, so that it may be expected that effects in the community reduce if the system indicates that the rating improves. Therefore, in principal it need to be based on empirical exposure-response relationships. However, because evidence regarding their influence on noise effects will be not available for all potentially relevant factors, rules based on one of three levels of empirical evidence can be incorporated:
  - I sufficiently precise empirical evidence;
  - II plausibility and empirical evidence, with limited quantitative uncertainty;
  - III plausibility and (some) empirical evidence, with limited quantitative uncertainty.

  Preferably information from the highest category is used, and the research that appears to be needed to strengthen the empirical basis of the rating system is recommended at the end of this introduction.
- The rating system needs to be consistent with the chosen noise metrics in the EU and the effect measures to rate the environmental noise. Specifically, L_{den} and L_{night} have been chosen as the noise metrics to be used for noise mapping in the EC (2002). Furthermore, annoyance and sleep disturbance are the health effects that are chosen as criteria for evaluating environmental noise. EU working groups have recommended exposure-response relationships to be used for estimating the prevalence of noise annoyance (EC-WG/2, 2002) and sleep disturbance (EC-WG/HSEA, 2004) on the basis of noise maps. For sleep disturbance, the working group presents relationships for two chronic effects related to L_{night}, namely noise-induced motility and self-reported sleep disturbance. The presented relationships for motility were derived for aircraft noise. For self-reported sleep

disturbance relationships are presented for aircraft, road traffic and railway noise. Here we focus on self-reported sleep disturbance, one reason for this choice being that only for this effect exposure-response relationships are available also for road traffic and railway noise. Given this background, the rating system need to be based on L_{den} and L_{night}, and need to predict noise annoyance and self-reported sleep disturbance.

- The rating system must be sensitive to changes in the acoustical situation that affect noise annoyance and sleep disturbance. To accomplish this, the set of predictors of annoyance and sleep disturbance will be extended beyond L_{den} and L_{night}, respectively, to improve the prediction on the basis of addition acoustical aspects. These extensions need to be consistent with the established relationships for noise annoyance and sleep disturbance that use only L_{den} or L_{night}, respectively, as predictor. Additional aspects that will be taken into account are sound insulation, quiet side of the dwelling, and ambient noise in the neighbourhood.

- The rating system must give insight in the acoustical situation that is as complete as needed for noise policy. Because often individuals are not exposed to noise from a single source, but to combined noise from various sources, a sufficiently complete rating system must be able to take into account total noise exposures, and the annoyance and sleep disturbance expected on the basis of this total exposure.

- In addition to indications of the acoustical climate in residential areas and the effects expected on the basis of exposures in and around home, there is a need to have specific information on the very high and the relatively low exposures. With respect to the very high exposures, it is important to quantify the number of individuals with an unacceptably high exposure. When a relatively large number of individuals with unacceptable exposures are clustered in a small area, we call this a hot spot. Unacceptability will be defined by convention and may be based on legal limits above which noise reduction is mandatory. Insight in areas where the environmental noise exposure is or can be relatively low, is useful for noise policy aiming at the improvement of quiet areas.

- The rating system need to be transparent and its usage in practice must be feasible. It must be transparent in the sense that it must show the overall effects to be expected given the noise maps, but in addition it must be clear how various acoustical aspects contribute to these overall outcomes. With respect to feasibility, it must be possible to define routines in a GIS system so that the noise ratings can be calculated automatically from the noise maps. The input information required for the calculation of the ratings need to be available after the mandatory noise mapping has been carried out (minimum required information), while it must be possible to take advantage of additional, more detailed information that is available to some of the municipalities in the EU (maximum usable information). Dealing with this requirement calls for a rating system that can incorporate detailed information, but also gives estimation procedures or defaults for cases where this information is not available.

This report is organised as follows. The next chapter (Ch 2) briefly discusses the EU noise metrics and their assessment. Then there are two chapters (Chs 3 – 4) that present relevant information that is available on exposure-effect relationships for noise annoyance and sleep disturbance. In these chapters it is not only discussed how these effects are related to noise exposure from a single type of source, but also how the effects are related to combined exposures. The subsequent chapter (Ch 5) introduces measures for identifying hot spots and for quiet areas. Then the method of incorporating sound insulation, quiet side of the dwelling and ambient noise level in the neighbourhood in the rating system that is primarily based on the exposure-effect relationships for individual and combined sources, is discussed (Ch 6). Finally, the rating system is presented as a stepwise procedure that can be read as a cookbook (Ch 7). Application of this procedure gives the following ratings of the environmental noise:

- **Overall noise climate in residential areas**: percentage highly annoyed (*%HA*);
- **Night-time noise climate in residential areas**: percentage highly sleep disturbed (*%HSD*);
- **Hot spots in residential areas**: (weighted) number of individuals above limit value $L(n_L)$;
- **Non-Quiet area**: percentage area with L_{den} > 50 dB(A) ($AREA_{50}$).

These four indicators together constitute the proposed system for rating environmental noise on the basis of noise maps. The indicators can be calculated for a city or parts of it (neighbourhoods), and for the present situation as well as for noise maps of possible future situations based on scenario's.

This report is intended primarily for firms which produce noise maps. It gives them the tool for adding an environmental noise rating system consistent with the EU policy to their noise mapping software. The report is not so much intended for the authorities of cities concerned with environmental noise. Hopefully they will see the result of the application of the tool to their city. The reader who is mainly interested in the tool and not so much in its background, can skip Chs 3 – 6, and go directly to the cookbook in the final chapter after reading a brief discussion of the most exposed facade in the next chapter.

Disclaimer and research needed: at this point in time the structure of the rating system that will be presented in the sequel appears to be solid and consistent with the requirements formulated in this chapter. However, it needs to be elaborated in some respects, and not all numerical values used are equally founded on empirical evidence. The points that could be elaborated are addressed in discussions in the subsequent chapters. In particular, procedures need to be developed to estimate the sound insulation on the basis of information at various levels of detail. The most important empirical research need concerns the influence of sound insulation, quiet side, and, less important from a quantitative point of view, ambient noise in the neighbourhood on noise annoyance, and the influence of sound insulation on (self-reported) sleep disturbance. These research questions could be addressed in a single joint European study.

Acknowledgement: we would like to acknowledge the helpful feedback with respect to hot spot detection which we received from Wolfgang Probst.

2 NOISE EXPOSURE

The EC Environmental Noise Directive (END) (EC, 2002) and related EU Position Papers (EC-WG/2, 2002; EC-WG/HSEA, 2004) on exposure – response relationships chose L_{den} (day-evening-night equivalent level) and L_{night} (night equivalent level) as the long term noise exposure metrics. L_{den} is used as the descriptor of the long term noise exposure with a view to predicting noise annoyance, and L_{night} is the descriptor of the noise exposure with a view to sleep disturbance. The assessment of these noise metrics is discussed in another position paper (EC-WG/AEN, 2003). Since there is ambiguity regarding some aspects of L_{den} and L_{night}, this chapter defines some important aspects of the assessment of these noise metrics. Choices are made with a view to the usage of the noise metrics for the prediction of the noise effects, since the rating system proposed here is meant to give indications of the noise effects. In order to be a proper basis for predicting noise effects, the noise metrics need to be defined as similar as possible to the metrics used in the studies from which exposure – response relationships were derived. Additional measures that describe the acoustical situation of a dwelling (sound insulation, exposure at the quiet side, and the ambient noise level in the neighbourhood) which are incorporated in the environmental noise rating system in combination with L_{den} and L_{night}, will be introduced in chapter 6.

L_{den}

L_{den} is defined in terms of the 'average' levels during daytime, evening and night, and applies a 5 dB(A) penalty to noise in the evening and a 10 dB(A) penalty to noise in the night.
The definition of L_{den} is as follows:

$$L_{den} \quad = \quad 10 \lg \left[(12/24).10^{LD/10} + (4/24).10^{(LE+5)/10} + (8/24).10^{(LN+10)/10}\right]$$

Here LD, LE, and LN are an A-weighted long term L_{Aeq} as defined in ISO 1996-2 (1987) for the day (7-19h), evening (19-23h), and night (23-7h) determined over the year at the most exposed facade at 4 m height for the incident sound (i.e., not including reflections by the facade of the dwelling of which the noise exposure is described).

L_{night}

L_{night} is the A-weighted long term L_{Aeq} as defined in ISO 1996-2 (1987) for the night (23-7h) determined over the year at the most exposed facade at 4 m height for the incident sound (i.e., not including reflections by the facade of the dwelling of which the noise exposure is described). Thus, L_{night} is the component in the definition of L_{den} denoted above by LN, and is an outdoor level.

Most exposed facade for assessment of L_{den} and L_{night}

The noise level at the most exposed facade is determined per dwelling for each type of source separately. This noise level is the highest level caused by the type of source concerned on an exterior wall (facades) of the dwelling. This is illustrated by figure 2.1. In both situations, the noise level on the 'most exposed facade' is 53 dB(A) for rail traffic noise and 50 dB(A) for road noise. It illustrates that the most exposed facade may be not the same for different sources. On the basis of practical considerations, the facade that is defined to be the most exposed facade for a source on the basis of the L_{den} values, is also taken to be the most exposed facade when assessing L_{night}.

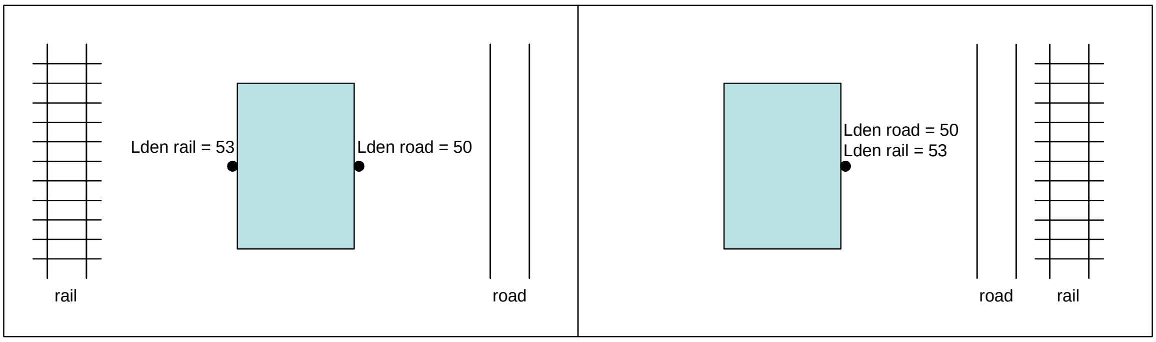

Figure 2.1: Two examples of the most exposed facades.

The levels at the most exposed facade as described above, are also the basis for calculating the total noise exposure from combined sources. Thus, in that calculation noise exposure levels may be combined from the same side of the dwelling (right part of figure 2.1), but in other cases levels found at different sides of the dwelling may be combined (left part of figure 2.1).

3 ANNOYANCE

The EU Position Paper on exposure-response relationships for noise annoyance (EC-WG/2 2002) discusses the annoyance measure to be used. It restricts its recommendations regarding exposure-response relationships to two related measures (percentage annoyed and percentage highly annoyed), but does not make a final choice between them. However, the discussion on the choice in the Position Paper, which is reproduced below, points towards the use of the percentage highly annoyed as the measure to be used. Therefore, here we adopt the percentage highly annoyed as the annoyance measure. Note however that relationships for other noise annoyance measures are also easily derived from the exposure-response model presented in the Appendix of the Position Paper, and that all that follows could easily be reformulated in terms of another annoyance measure.

The percentage highly annoyed (*%HA*) is defined as the percentage of responses exceeding the cut-off of 72 on a 0-100 scale of annoyance, with 0 corresponding to no annoyance at all, and 100 corresponding to extreme annoyance.

3.1 ANNOYANCE EXPOSURE-RESPONSE RELATIONS PER TYPE OF SOURCE

The Position Paper recommends the use of the following relationships for the estimation of the percentage highly annoyance (*%HA*) on the basis of the noise exposure of dwellings:

%HA for aircraft

$$\%HA = -9.199\times10^{-5} (L_{den} - 42)^3 + 3.932\times10^{-2} (L_{den} - 42)^2 + 0.2939 (L_{den} - 42);$$

%HA for road traffic

$$\%HA = 9.868\times10^{-4} (L_{den} - 42)^3 - 1.436\times10^{-2} (L_{den} - 42)^2 + 0.5118 (L_{den} - 42);$$

%HA for railways

$$\%HA = 7.239\times10^{-4} (L_{den} - 42)^3 - 7.851\times10^{-3} (L_{den} - 42)^2 + 0.1695 (L_{den} - 42).$$

The above relationships are valid in the range $42 \leq L_{den} \leq 75$ dB(A). Below 42 dB(A) the percentage highly annoyed is assumed to be nihil. Figure 3.1 shows the corresponding curves and table 1 give the numerical value for *%HA* at various levels of L_{den}. The figures also show the 95% confidence intervals around the curves (dotted lines). Since the annoyance curves have rather narrow confidence intervals, the location of these curves in the entire population is known rather accurately.

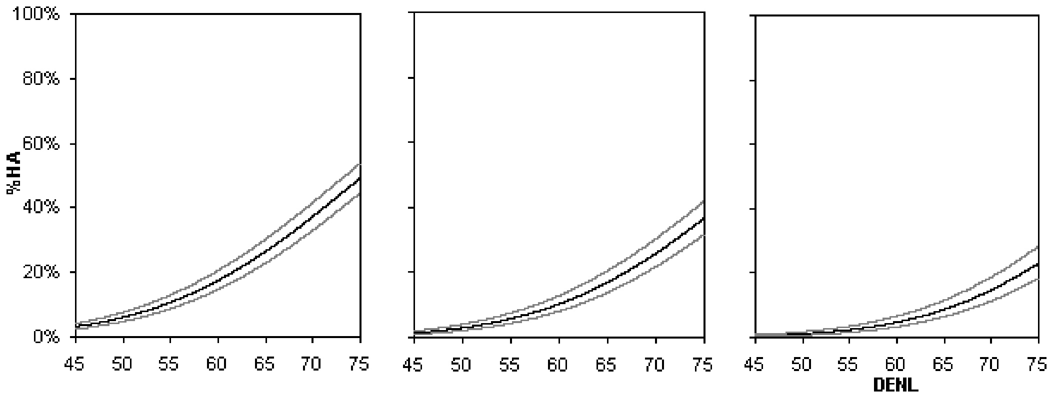

Figure 3.1: For aircraft, road traffic and railways, *%HA* as a function of L_{den}, together with the 95% confidence intervals.

Table 1: ***%HA* at various noise exposure levels (L_{den}) for aircraft, road traffic, and railways**

L_{den}	Aircraft	Road traffic	Railways
45	1	1	0
50	5	4	1
55	10	6	2
60	17	10	5
65	26	16	9
70	37	25	14
75	49	37	23

3.2 RELATION OF ANNOYANCE TO COMBINED EXPOSURES

In many cases people are exposed not to either aircraft, road traffic or railway noise, but to a combination of these types of noises. The annoyance equivalents model (Miedema, 2004) describes how the annoyance caused by the total, combined exposure can be calculated. Briefly, the procedure based on the model is to translate the noise from the individual sources into the equally annoying sound levels of a reference source (road traffic), and then to sum these levels. Figure 3.2 illustrates this for two different noise sources A and B. The noise levels from these sources are L_A and L_B, respectively. Source A (road traffic) is selected as the reference. In order to calculate the total noise annoyance, L_B is transformed into the equally annoying level of A, re(L_B) (read: *road equivalent* of L_B), as shown in the figure. Then L_A and re(L_B), are added on an energy basis, giving L_T. The corresponding annoyance from the two combined sources is found by using the exposure - annoyance relationship of reference source A, with exposure L_T. Thus, the model first translates the noise from the individual sources into the equally annoying sound levels of a reference source, road traffic, and then sums these levels giving total level L_T. The annoyance from the combined sources is found by substituting exposure L_T in the road traffic exposure – annoyance relationship.

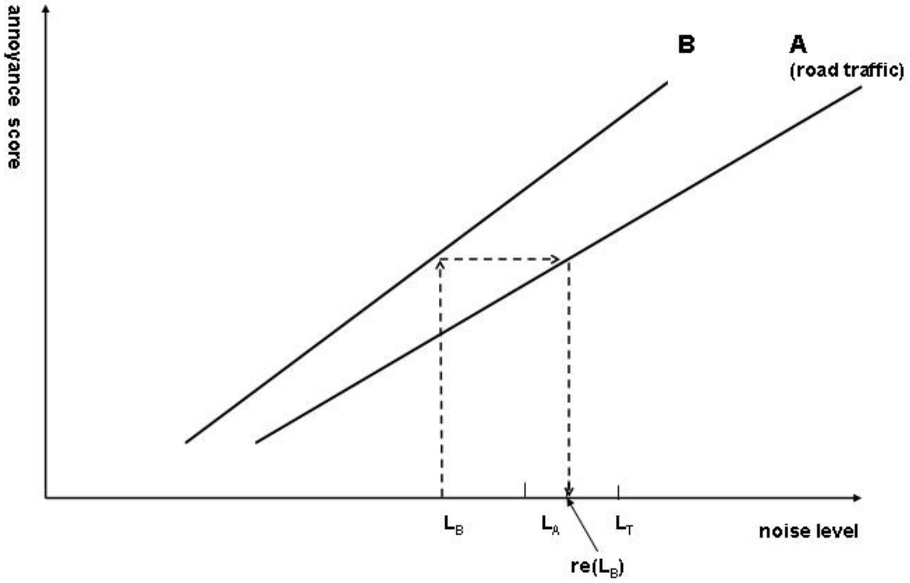

Figure 3.2: Illustration of the annoyance equivalents model (see text)

The assessment of the total noise level and the corresponding percentage highly annoyed can be broken down in the following 5 steps:

%HA for combined exposures

1. Assess L_{den} for aircraft, road traffic, and railways ($L_{den,air}$, $L_{den,road}$ and $L_{den,rail}$).

2. Calculate the percentage highly annoyed for aircraft, and for railways.

   $\%HA_{air} = -9.199\times10^{-5}\,(L_{den} - 42)^3 + 3.932\times10^{-2}\,(L_{den} - 42)^2 + 0.2939\,(L_{den} - 42);$

   $\%HA_{rail} = 7.239\times10^{-4}\,(L_{den} - 42)^3 - 7.851\times10^{-3}\,(L_{den} - 42)^2 + 0.1695\,(L_{den} - 42).$

3. Calculate the equally annoying road traffic levels for aircraft and for railways as follows (i is either air or rail):

   $$\mathrm{re}(L_{den,i}) = \begin{cases} 46.85 + 168.9\,\mathbf{F}(\%HA_i) - \dfrac{0.8843}{\mathbf{F}(\%HA_i)} & \text{for } L_{den,i} > 42 \\ L_{den,i} & \text{for } L_{den,i} \leq 42 \end{cases}$$

   where

   $$\mathbf{F}(x) = \left(-2.374\times10^{-4} + 1.05\times10^{-4}\,x + \sqrt{2\times10^{-7} - 5\times10^{-8}\,x + 1.11\times10^{-8}\,x^2}\right)^{1/3}.$$

4. Calculate the total noise level:

   $$L_{den,T} = 10\times\lg\left(10^{0.1\times\mathrm{re}(L_{den,air})} + 10^{0.1\times L_{den,road}} + 10^{0.1\times\mathrm{re}(L_{den,rail})}\right).$$

5. Calculate the percentage highly annoyed for the combined, multiple sources:

   $$\%HA = 9.868\times10^{-4}\,(L_{den,T} - 42)^3 - 1.436\times10^{-2}\,(L_{den,T} - 42)^2 + 0.5118\,(L_{den,T} - 42).$$

In the final step, the exposure-response function for road traffic presented in the preceding section is applied to the total noise level $L_{den,T}$, because the total level is expressed as the road traffic level that would give equal annoyance as the combination of exposures concerned.

3.3 DISCUSSION

Choice of the annoyance measure

The following discussion summarizes some arguments presented in a similar discussion in the Position Paper on noise annoyance (EC-WG/2, 2002).

%HA has been most widely used. An important practical advantage over the percentage annoyed (*%A*), which uses 50 as the cut off on a 0 – 100 annoyance scale, is that calculation of the *%A* does require very low levels down to L_{den} = 37 dB(A) to be assessed, while determination of the number of highly annoyed persons (*%HA*) does not require information on levels with L_{den} < 42 dB(A). Experience made clear that the higher sensitivity of *%HA* to changes in the higher range of L_{den} and the lower sensitivity to changes in the lower range of L_{den} actually may be an advantage. Substantive reduction of any prevalence measure of annoyance (based on *%HA* or *%A*) requires improvements in the lower part of the noise exposure range, because the largest part of the population comes in that part of the range. There is no danger of neglecting quiet areas as a consequence of using *%HA* as the annoyance descriptor, if there is a separate indicator stimulating the preservation and extension of quiet areas (e.g. $AREA_{50}$)

Application and limitations

The following discussion is partly based on a similar discussion in the Position Paper on noise annoyance (EC-WG/2, 2002).

The exposure-response functions and their curves recommended are only to be used for aircraft, road traffic, and railway noise and for assessment of long term stable situations. They are to be utilised for strategic assessment, in particular in the context of Annex III of END, in order to assess the effects of noise on populations in terms of annoyance. They can be used in target setting, in translating noise maps into overviews of numbers of persons highly annoyed, in cost-benefit analysis and Environmental Health Impact Assessment. When used in Environmental Health Impact Assessment, they give insight in the situation that is expected in the long term. They are not applicable to local, complaint-type situations were idiosyncratic features play an important role, or to the assessment of the short-term effects of a change of noise climate. The curves have been derived for adults. The curves are not recommended for specific sources such as helicopters, military low-flying aircraft, train shunting noise, shipping noise or aircraft noise on the ground [taxi-ing]. There are indications that annoyance of aircraft noise at a given exposure level has increased. This may necessitate adoption of higher curves or curves that predict higher annoyance in the future but sufficient evidence to do so is lacking at present.

The critical property underlying the model for the annoyance of combined sources is ‘independence’ of the contributions to annoyance. Important violations of this assumption are expected only in a limited number of practical situations. For example, independence is violated if a tonal sound combined with little or no road traffic noise is more annoying than the same tonal sound with a higher level of road traffic noise. This may actually occur if the tonal sound is masked in the latter case. A similar phenomenon may be found with very low frequency noise, or impulsive noise instead of tonal noise. In these cases the annoyance reduction caused by the masking of the very irritating sound may outweigh the annoyance increase caused by the higher road traffic noise. The use of the procedure for calculating annoyance from combined sources is not recommended for these specific situations.

Temporary patch
Steps 2 and 3 in the procedure for calculating *%HA* for combined exposures actually deviates numerically slightly from the outcome of the following steps which are in principle the proper steps:

2'. Calculate the annoyance level for aircraft, and for railways[1]:

$$A_{air} = 2.17\, L_{den,air} - 91.4$$

$$A_{rail} = 2.10\, L_{den,rail} - 110.1.$$

3'. Calculate the equally annoying road traffic levels for aircraft, and for railways:

$$\mathrm{re}(L_{den,air}) = (A_{air} + 107.0) / 2.22$$

$$\mathrm{re}(L_{den,rail}) = (A_{rail} + 107.0) / 2.22.$$

The need for replacing steps 2' and 3' is caused by two details in the (polynomial approximations of) the exposure – response relationships that give *%HA* as a function of L_{den}. The first point is that at low exposure levels the polynomial approximation of the *%HA* curve for aircraft noise underestimates the actual model curve. The second point is that the exposure – response models were fitted separately for the different types of transportation so that the estimated variance of the annoyance scores at a given exposure level, was free to vary between the three types of sources. Actually rather similar variances were found but they were not exactly equal. Due to these two points (deviation of a polynomial approximation and not exactly equal estimates of variances), the calculated *%HA* for a single source situation with a low aircraft noise level differs depending on whether it is calculated directly with the exposure – response curve for the single source or indirectly with the procedure for combined exposures (for which is it a limit situation to which the procedure also applies). A similar point holds for railway noise. This is undesirable. The principle solution is not difficult to realise and would require that the exposure – response relationships for the single sources are again fitted on the basis of the same still available data and that then the polynomial approximations are again determined, taking into account the above two points. Although the result would only slightly deviate from the existing, above given relationships for single sources, at present the easiest approach is to replace in the procedure for combined exposures the proper steps 2' and 3', by the 'patch' steps 2 and 3. In contrast with the proper procedure (steps presented here), which can be used also when in the end other annoyance measures are determined (e.g. percentage annoyed instead of *%HA*) the patch can be used only for calculating *%HA*. Hopefully in due time, the single source relationships can be re-established in the described manner so that the patch can be replaced by the proper step.

Additional points of consideration and recommend literature
The description in sections 3.1 and 3.2 is based on research published in two articles (Miedema & Oudshoorn, 2001; Miedema, 2004). The description is restricted to the three major transportation noise sources (air, road, and rail traffic). Stationary sources (e.g. industry) could be incorporated in the same framework using results published by Miedema & Vos (2004).
In addition to acoustical factors, noise annoyance is also related to personal characteristics. In an analysis of the combined data from many studies, Miedema and Vos (1999) found

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[1] The linear relationships do not have the observed annoyance score as the dependent variable, but the mean of the corresponding (latent) variable with a normal distribution, which may have negative values.

that in particular noise sensitivity, fear of the source (in case of aircraft), and to a lesser extent, age influence noise annoyance. Little influence was found of economic dependency on the noise (e.g. working at the airport), education level, occupation status, homeownership, use of the noise source (frequent flyer or not). It is important to distinguish the influence of such factors on noise annoyance (which have been found to be small for e.g. economic dependency), and acceptance of noise annoyance (which may depend strongly on economic dependency). Also expectation regarding future developments of the noise exposure appears to influence the annoyance. There is some debate as to the exact form of influence (moderator or additive factor) of one of the most important factors, noise sensitivity (Miedema and Vos, 2004; Stansfeld et al., 2005)

There are indications that there has been a trend towards higher annoyance for aircraft noise at the same L_{den} level. There are no definite results with respect to this issue. The first publication drawing attention to this issue was Guski (2004).

Children appear to be a vulnerable group in several respects. In particular, their cognitive development may be adversely affected by exposure to (aircraft) noise. It appears necessary to give special attention to the noise exposure of vulnerable groups and therefore evaluate the noise exposures of e.g. schools. The results of a recent European study on effect of noise on children are published by Stansfeld et al. (2005)

4 SLEEP DISTURBANCE

The EU Position Paper on exposure-response relationships for noise-induced sleep disturbance (EC-WG/HSEA, 2004) presents relationships for two chronic effects related to L_{night}, namely noise-induced motility and self-reported sleep disturbance. The presented relationships for motility were derived for aircraft noise. For self-reported sleep disturbance relationships are presented for aircraft, road traffic and railway noise. Here we focus on self-reported sleep disturbance, one reason for this choice being that only for this effect exposure-response relationships are available also for road traffic and railway noise.

The EU Position Paper recommends for self-reported sleep disturbance exposure-response relationships for three related measures (percentages –at least – a little sleep disturbed, sleep disturbed, and highly sleep disturbed), but does not make a choice between them. By analogy of the choice for annoyance, here we adopt the percentage highly sleep disturbed as the sleep disturbance measure. Note however that relationships for other self-reported sleep disturbance measures are also easily derived from the exposure-response model presented in the report underlying the Position Paper, and that all that follows could easily be reformulated in terms of another self-reported sleep disturbance measure.

The percentage highly sleep disturbed (*%HSD*) is defined as the percentage of responses exceeding the cutoff of 72 on a 0-100 sleep disturbance scale, with 0 corresponding to no sleep disturbance at all, and 100 corresponding to extreme self-reported sleep disturbance.

4.1 SLEEP DISTURBANCE EXPOSURE-RESPONSE RELATIONS PER TYPE OF SOURCE

The Position Paper recommends the use of the following relationships for the estimation of the percentage highly sleep disturbed (%HSD) on the basis of the noise exposure of dwellings:

%HSD for aircraft

$$\%HSD = 18.147 - 0.956\, L_{night,air} + 0.01482\, L_{night,air}^2;$$

%HSD for road traffic

$$\%HSD = 20.8 - 1.05\, L_{night,road} + 0.01486\, L_{night,road}^2;$$

%HSD for railways

$$\%HSD = 11.3 - 0.55\, L_{night,rail} + 0.00759\, L_{night,rail}^2.$$

The above relationships can be applied in the range $40 \leq L_{night} \leq 70$ dB(A). The relationships are based on data in the L_{night} range 45-65 dB(A) and are expected to give approximations also for lower exposures (40-45 dB(A)) and higher exposures (65-70 dB(A)). Below 40 dB(A) the percentage highly sleep disturbed is assumed to be nihil.

Figure 4.1 shows the corresponding curves and table 1 give the numerical value for *%HSD* at various levels of *L_{night}*. The figures also show the 95% confidence intervals around the curves (dotted lines).

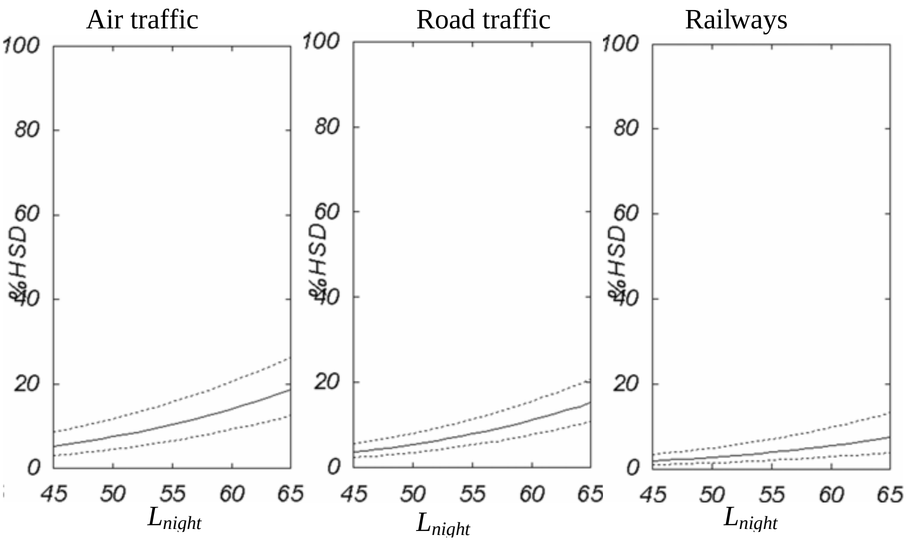

Figure 4.1: For aircraft, road traffic and railways *%HSD* as a function of *L_{night}*, together with the 95% confidence intervals.

Table 4.1: *%HSD* at various noise exposure levels (*L_{night}*) for aircraft, road traffic, and railways

L_{night}	Aircraft	Road traffic	Railways
40	4	3	1
45	5	4	2
50	7	5	3
55	10	8	4
60	14	11	6
65	19	15	8
70	24	20	10

4.2 RELATION OF SLEEP DISTURBANCE TO COMBINED EXPOSURES

Also at night, in many cases people are not exposed to either aircraft, road traffic or railway noise, but to a combination of these types of noises. The annoyance equivalents model which describes how the annoyance caused by the total, cumulative exposure can be calculated has been described in the previous chapter. The approach taken for self-reported sleep disturbance is completely analogue. For explanation we refer to the description and the discussion in sections 3.2 en 3.3, and here we present only the stepwise procedure, now for self-reported sleep disturbance:

%HSD for combined exposures

1. Assess L_{night} for aircraft, road traffic and railways ($L_{night,air}$, $L_{night,road}$ and $L_{night,rail}$);

2. Calculate the percentage highly sleep disturbed for aircraft and for railways:

$$\%HSD_{air} = 18.147 - 0.956\, L_{night,air} + 0.01482\, L_{night,air}^2;$$

$$\%HSD_{rail} = 11.3 - 0.55\, L_{night,rail} + 0.00759\, L_{night,rail}^2.$$

3. Calculate the equally sleep-disturbing road traffic levels for aircraft and for railways as follows ('*i*' is either air or rail):

$$\text{re}\ (L_{\text{night},i}) = \begin{cases} 35.33 + \sqrt{67.29(\%HSD_i) - 151.5} & \text{for } L_{night,i} > 40 \\ L_{night,i} & \text{for } L_{night,i} \leq 40 \end{cases}$$

4. Calculate the total night-time noise level:

$$L_{night,T} \quad = \quad 10 \times \lg\,(10^{0.1 \times \text{re}(L_{night,air})} + 10^{0.1 \times L_{night,road}} + 10^{0.1 \times \text{re}(L_{night,rail})})$$

5. Calculate the percentage highly sleep disturbed for the combined, multiple sources:

$$\%HSD \quad = 20.8 - 1.05\, L_{night,T} + 0.01486\, L_{night,T}^{\,2}.$$

In the final step, the exposure-response function for road traffic presented in the preceding section is applied to the total night-time noise level $L_{night,T}$ because the total level is expressed as the road traffic level that would give equal self-reported sleep disturbance as the combination of exposures concerned.

4.3 DISCUSSION

Choice of the self-reported sleep disturbance as the effect measure

A conceptual framework for noise-induced sleep disturbance is presented in figure 4.1 (cf. Ising et al., 1999). This framework gives a rough outline of steps in the development of effects of night-time noise. The framework suggests the sequential occurrence of the immediate processing of noise, instantaneous arousal/stress reactions and changes in one night and the day after, chronic (possibly reversible) changes, and an increased risk of (irreversible) health effects. This process is initiated by noise exposure during the sleep period, and depends on the state and characteristics of the individual. Furthermore, there is feedback concerning the occurrence of acute and chronic effects that influences the occurrence of further (stress-related) effects. The framework does not imply that instantaneous effects necessarily contribute to chronic changes or long term health effects, or that chronic changes necessarily contribute to long term health effects. Recovery mechanisms can restore balances and prevent the occurrence of further effects.

A comprehensive assessment of the effects of noise on sleep would consider all three effect stages in figure 4.1 (instantaneous changes and changes in one night and the day after, chronic changes, long term health effects). The effects in figure 4.1 for which there is a sufficient basis to establish (provisional) exposure-response relationships, are in italics: the instantaneous effects (onset of) motility; micro-arousals and (conscious) awakening and the chronic effects increase of mean motility during sleep and self-reported sleep disturbance.

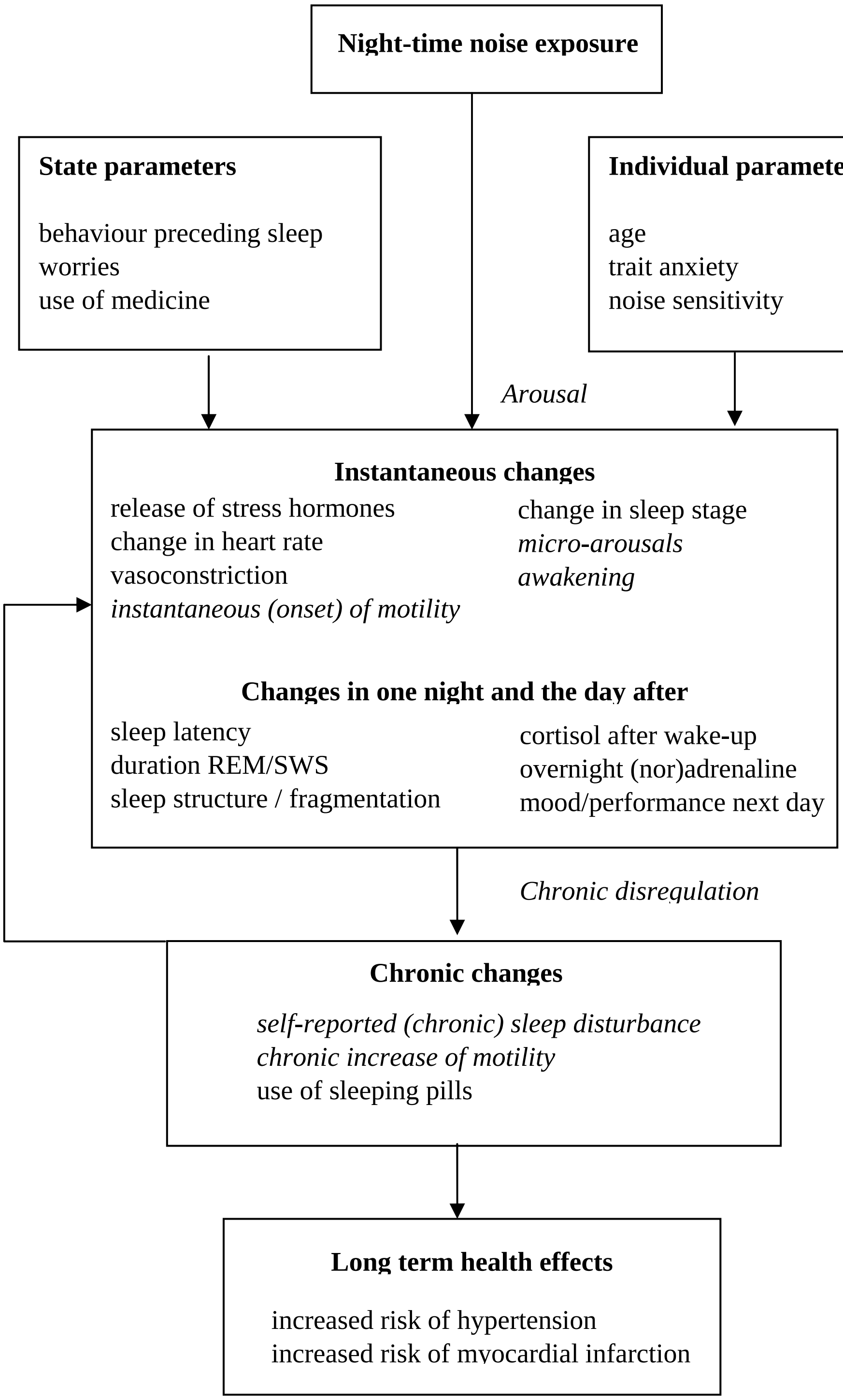

Figure 4.2: Framework for the study of noise-induced sleep disturbance. The effects mentioned are examples and not necessarily proven effects of noise on sleep. Exposure-response relationships have been established for the effects printed in italics, with the exception of self-reported sleep disturbance, only for aircraft noise. Relationships established for myocardial infarction do not specifically relate this effect to night-time noise. Relations for self-reported sleep disturbance have been established for aircraft, road traffic and railway noise.

Only the chronic effects mean motility and self-reported sleep disturbance are directly related L_{night}, and only for self-reported sleep disturbance relationships are also available for road traffic and railway noise. This is an important reason for choosing self-reported sleep disturbance as the effect measure of sleep disturbance.

Application and limitations
The description in sections 4.1 and 4.2 is based on research published in two articles (Miedema and Vos, 2007; Miedema, 2004). The exposure-response functions and their curves recommended are only to be used for aircraft, road traffic, and railway noise and for assessment of long term stable situations. They are to be utilised for strategic assessment, in particular in the context of Annex III of END, in order to assess the effects of night-time noise on populations in terms of self-reported sleep disturbance. They can be used in target setting, in translating noise maps into overviews of numbers of persons highly sleep disturbed, in cost-benefit analysis and Environmental Health Impact Assessment. When used in Environmental Health Impact Assessment, they give insight in the situation that is expected in the long term. They are not applicable to local, complaint-type situations were idiosyncratic feature play an important role, or to the assessment of the short-term effects of a change of noise climate. The curves have been derived for adults. The curves are not recommended for specific sources such as helicopters, military low-flying aircraft, train shunting noise, shipping noise or aircraft noise on the ground [taxi-ing]. There are indications that also the self-reported sleep disturbance of aircraft noise at a given exposure level has increased. This may necessitate adoption of curves that predict higher sleep disturbance in the future, but at present sufficient evidence to do so is lacking. The relationships for self-reported sleep disturbance are weaker than the relationships presented for noise annoyance, in particular the relationships for self-reported sleep disturbance by aircraft noise. Similar comments as made with respect to the model of the annoyance from combined sources, hold for the approach used to predict the self-reported sleep disturbance caused by the total combined night-time noise.

5 UNACCEPTABLE EXPOSURES AND QUIET AREAS

The annoyance and sleep disturbance indicators (*%HA* and *%HSD*) describe the overall and night-time acoustic climate in residential areas. In addition there is a need to have specific information on the exposures that are so high that they are considered to be unacceptable and specific information on the quiet areas. The problem of unacceptable exposures can be quantified by counting the number of individuals above a high limit value. Counting very highly exposed persons and assessing the quiet area supplement the insight in the general residential acoustic climate as indicated by the number of highly annoyed and the number of highly sleep disturbed. These additional numbers focus on the extremes to guide separate actions aiming at eliminating the very high exposures, or preserving or extending the quiet area. Actions to eliminate unacceptable exposures may be motivated by a principle that everybody has the right to a certain minimal level of protection against environmental noise, which may be codified in regulations setting noise limits. Actions to preserve or extend the quiet area may be motivated by goals concerning the quality of (urban) recreational areas.

5.1 UNACCEPTABLE RESIDENTIAL EXPOSURES (HOT SPOTS)

A straightforward indicator of the problem of unacceptable exposures is the number of individuals with L_{den} above limit value L.

Even though all exposures above limit L may be considered to be unacceptable, due to practical limitations it may not be possible to eliminate these exposures in a limited period. To guide actions first towards the improvement of the exposures that are most in excess of the limit, a weighting function may be introduced. There are no widely accepted weighting functions so that it must be decided locally whether such a function is considered useful and which function is preferred. Two options for families of weighting functions are the linear weighting functions and the exponential weighting functions. The linear weighting function gives the weight above limit L as follows:

$$W(L_{den}) = 1 + a\,(L_{den} - L),$$

with $a > 0$, while setting $W(L_{den}) = 0$ below the limit. The exponential weighting function gives the weight above limit L as follows:

$$W(L_{den}) = 10^{a(L_{den} - L)}$$

with $a > 0$, while setting $W(L_{den}) = 0$ below the limit.

The indicator of the prevalence of unacceptable exposures, i.e. the (weighted) number of persons above a limit L denoted by n_L, is the basis for the detection of hot spots. This number can be assessed for a whole municipality or for neighbourhoods, but also for small areas. Hot spots are defined as small areas with a high number of unacceptably exposed persons, i.e. a high value of n_L. Such spots may be found by calculating for all (partially overlapping) square windows of, e.g., size 100 m × 100 m, which together cover the total area of the municipality, ni.. Then, (clusters of) squares with high n_L are the hot spots.

5.2 QUIET AREAS

The indicator of non-quiet area is the percentage of an area with L_{den} > 50 dB(A) ($AREA_{50}$). When the value of this indicator decreases, the presence of quiet area has increased. We chose this indicator instead of its complement, the percentage of area with L_{den} < 50 dB(A), in order that a lower value means a better situation for all four indicators in the rating system. The indicator can be assessed for a whole municipality or for neighbourhoods irrespective of the further characteristics of the area. With a view to recreation, is may be useful to determine also the percentage of area otherwise suited for recreation with

L_{den} > 50 dB(A). For example, the protection of quiet areas may focus on parks, and on areas with walking and bicycle routes.

6 ADDITIONAL ACOUSTICAL FACTORS

In addition to the noise level at the most exposed facade (L_{den} and L_{night}), there are a number of factors that affect noise annoyance and self-reported sleep disturbance. For annoyance three additional acoustical factors are considered:

- sound insulation
- quiet side
- ambient noise level in the vicinity of the dwelling

For sleep disturbance, only the noise insulation of the bedroom is considered.

The exposure-effect curves for annoyance and sleep disturbance are based on the 'average' situation for each of the above factors (in the study samples on which the curves are based). If a dwelling has, e.g., a higher sound insulation than average, noise annoyance of its inhabitants will be less than expected on the basis of the exposure-effect curve. On the other hand, if a dwelling has a lower sound insulation than the average dwelling, noise annoyance of its inhabitants will be higher than expected on the basis of the exposure-effect curve. The method to take these additional factors into account used here, is to adjust the noise exposure level ($L_{den,i}$ and $L_{night,i}$). The adjusted noise exposure levels ($L_{den,i}$' and $L_{night,i}$') can be used with the same exposure-effect curves for annoyance and sleep disturbance presented in the previous chapters to estimate annoyance and sleep disturbance. This is accomplished by defining the adjustments as deviations from the 'average' situation, as will be discussed in more detail below.

In general the effect of an additional factor (e.g. sound insulation) will dependent on the outdoor noise level. Furthermore, the effects of additional factors are assumed to be linear and independent. More specifically, on the basis of these considerations, the adjusted $L_{den,i}$' and $L_{night,i}$' are calculated as follows:

$$\begin{aligned} L_{den,i}' = L_{den,i} + \\ & a_{I,i}(I_i - \overline{I_i})L_{den,i} + b_{I,i}(I_i - \overline{I_i}) + \\ & a_{Q,i}(Q_i - \overline{Q_i})L_{den,i} + b_{Q,i}(Q_i - \overline{Q_i}) + \\ & a_{A,i}(A - \overline{A_i})L_{den,i} + b_{A,i}(A - \overline{A_i}) \end{aligned} \tag{1}$$

I_i = lowest insulation for source type *i* of bed/living room at the most exposed facade [dB(A)];
Q_i = difference between most and least exposed facade for source type *i* [dB(A)];
A = ambient noise level within a radius of 200 m around the dwelling [dB(A)].
$\overline{I}_i$ = 'average' insulation of dwellings for source type *i* [dB(A)];
$\overline{Q_i}$ = 'average' difference between most and least exposed facade for source type *i* [dB(A)];
$\overline{A}_i$ = 'average' ambient noise level within 200 m radius of a dwelling for source type *i* [dB(A)].

$$L_{night,i}' = L_{night,i} + a_{I_b,i}(I_{b,i} - \overline{I_{b,i}})L_{night,i} + b_{I_b,i}(I_{b,i} - \overline{I_{b,i}}) \tag{2}$$

$I_{b,i}$ = lowest insulation for source type *i* of bedrooms at the most exposed facade [dB(A)].

$\overline{I_{b,i}}$ = 'average' bedroom insulation of dwellings for source type *i*.

The additional factors are discussed in more detail below.

6.1 ADDITIONAL FACTORS AND LDEN

L_{den} is the metric used to predict noise annoyance. This section presents an elaboration of this metric which incorporates other factors that influence annoyance. The factors taken into account are sound insulation, quiet side, and ambient noise in the neighbourhood.

6.1.1 Insulation

If the insulation of the dwelling is higher than average, the indoor noise levels will be lower than average. Consequently, with the same outdoor exposure, an insulation higher than average will cause the noise annoyance to be less than average. The insulation as it is meant here is the maximum insulation that can be obtained by the inhabitants of a dwelling, i.e., with the windows closed. The actual beneficial effect of insulation on noise annoyance will depend on the ventilation system in the dwelling (briefly discussed below).

If we consider only the effect of the insulation (suppose the quiet side and ambient noise are average), equation 1 reduces to:

$$L_{den,i}' = L_{den,i} + a_{I,i}(I_i - \overline{I}_i)L_{den,i} + b_{I,i}(I_i - \overline{I}_i)$$

In principle, the parameters $a_{I,i}$ and $b_{I,i}$ can be estimated on the basis of empirical data. Here it is assumed that the parameters $a_{I,i}$ and $b_{I,i}$ do not dependent on the type of noise source, so that they can be written as a_I and b_I. Actually, there is very little data available for estimating the parameters. The tentative assignment of values to the parameters is discussed below.

Parameter estimation

The percentage of highly annoyed by noise starts to increase above zero around 45 dB(A). Because the percentage of highly annoyed is very low below 45 dB(A), sound insulation is assumed to start having a beneficial effect from 45 dB(A) on. The beneficial effect of noise insulation will increase when the outdoor noise level is higher. The beneficial effect of sound insulation is maximal for high sound insulation values in a situation with high outdoor noise levels. We assume that at a very high exposure level, a high extra insulation is equivalent to a reduction of the (outdoor) exposure that is less than the value of the extra insulation but equal to a substantial part of it. More specifically, we assume that extra noise insulation of 15 dB(A) at 75dB(A) would correspond to a reduction of the outdoor L_{den} with 10 dB(A). This leads to two equations from which we can solve factors a_I and b_I:
$a_I \times 15 \times 75 + b_I \times 15 = -10$
$a_I \times 15 \times 45 + b_I \times 15 = 0$
which gives: $a_I = -0.022$ and $b_I = 1$.
It is assumed that there is a limit to the positive effect of increasing sound insulation and to the negative effect of very poor sound insulation. More specifically, it is assumed that the (absolute) effect is maximal, when $\left| I_i - \overline{I}_i \right| = 15$ and remains at the same level for higher absolute differences.
Furthermore, we do not know what happens at extremely high levels (L_{den} > 75 dB(A)), but assume that the effect of insulation will not continue to increase.

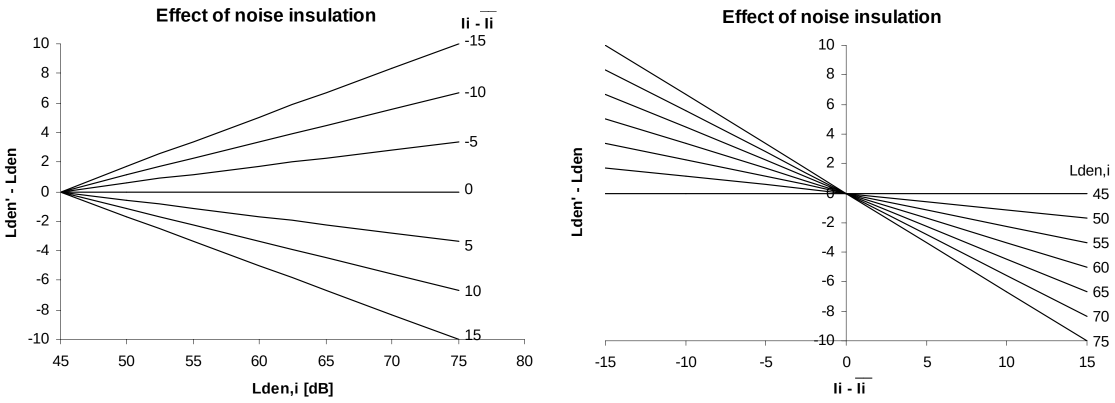

Figure 6.1: Effect of sound insulation on the difference between L_{den}' and L_{den} as function of L_{den} (left figure) and as function of the relative insulation value (right figure).

The effect of sound insulation based on the above assumptions is illustrated in figure 6.1.

Discussion
The beneficial effect of sound insulation depends on the possibility to ventilate sufficiently when the windows are closed (at the most exposed facade). If then the ventilation is poor, occupants will open windows, causing the noise insulation to drop. If windows are to be kept closed even though the ventilation is not adequate, noise still will be considered to be annoying because it is the cause of the situation with inadequate ventilation. Therefore, the beneficial effect of sound insulation will be much smaller if the ventilation with closed windows is not sufficient.
In some cases, the most exposed facade is closed, i.e., it has no windows that can be opened. These facades may give a high insulation. If the following conditions are fulfilled, the closed facade can be excluded when determining the most exposed facade for each individual type of source (see Ch 2), i.e., then the most exposed facade is the non-closed facade with the highest noise load. The first condition is that the ventilation in the dwelling with the closed facade is sufficient. The second condition is that layout of the dwelling is designed so that all bedrooms and the living room do have windows that can be opened.

6.1.2 Quiet side

When there is a quiet side at the dwelling, the occupants can 'escape' to some extent from the noise levels at the most exposed facade. This will reduce annoyance in comparison to situations when there is no such escape. In order to be able to escape from the noise at the most exposed facade, the noise exposure due to all noise sources has to be low at the quiet facade. Therefore, in the evaluation of the quiet side for one source type, the outdoor noise level from all noise sources ($L_{outdoor}$) has to be considered. This outdoor noise level is calculated with the rules regarding combined sources described in subsection 3.2. The outdoor noise level is the 'energetic sum' of the road equivalent noise levels from the individual sources (re($L_{den,i}$)):

$$L_{outdoor} = 10\times\lg(10^{0.1\times\mathrm{re}(L_{den,air})} + 10^{0.1\times L_{den,road}} + 10^{0.1\times\mathrm{re}(L_{den,rail})})$$

The lowest outdoor exposure level of a dwelling, min($L_{outdoor}$), is determined by calculating $L_{outdoor}$ for points on all the facades of the dwelling and taking the lowest value. The measure for the beneficial effect of a quiet side when exposed to source type *i*, denoted by Q_i, is the difference between the exposure at the most exposed facade for noise source i and $\min(L_{outdoor})$. Because the lowest outdoor exposure level is a road equivalent noise level, also the road equivalent noise level at the most exposed facade ($\mathrm{re}(L_{den,i})$) is used, giving:

$$Q_i = \mathrm{re}(L_{den,i}) - \min(L_{outdoor})$$

$\mathrm{re}(L_{den,i})$ = road equivalent noise level from source type i [dB(A)];
$L_{outdoor}$ = cumulated outdoor noise level [dB(A)]

The quietest side may have a higher road equivalent noise level than the road equivalent noise level of the individual source concerned, because the quietest side is defined on the basis of the combined exposure of the various sources. Consequently, $\min(L_{outdoor})$ may exceed $\mathrm{re}(L_{den,i})$ so that Q_i may be negative.

Example

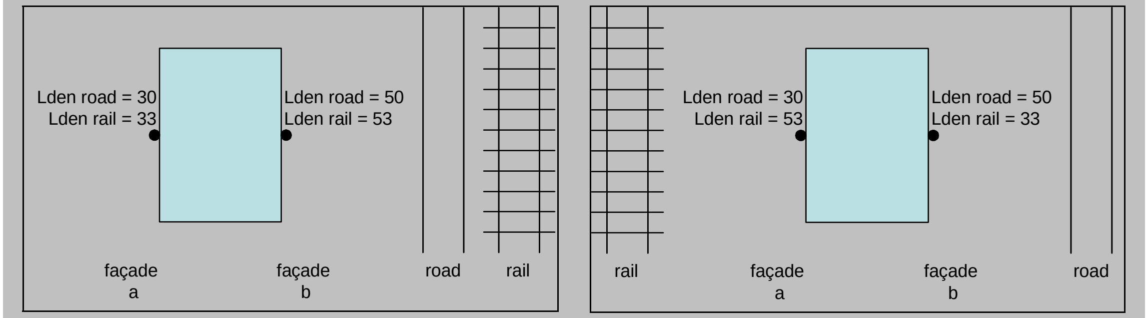

Figure 6.2: Illustration of the calculation of the quiet side correction for rail traffic noise.

The calculation of Q_{rail} is illustrated by calculations for the two situations in figure 6.2 where the attention is restricted to two facades. In the left situation, $L_{den,rail}$ is 53 dB, which gives an equal annoying road noise level ($\mathrm{re}(L_{den,rail})$) of 46.0 dB. The lowest total outdoor noise level on a façade of the dwelling, $L_{outdoor}$, is 34.7 dB. Q_{rail} in the left situation then is $\mathrm{re}(L_{den,rail}) - \min(L_{outdoor}) = 46.0 - 34.7 = 11.3$ dB. In the right situation, $L_{den,rail}$ is also 53 dB, which gives an equal annoying road noise level ($\mathrm{re}(L_{den,rail})$) of 46.0 dB. The lowest total outdoor noise level on a façade, $L_{outdoor}$, is 46.1 dB. Q_{rail} in the right situation then becomes $\mathrm{re}(L_{den,rail}) - \min(L_{outdoor}) = 46.0 - 46.1 = -0.1$ dB.

If we consider only the effect of the quiet side (suppose sound insulation and ambient noise are average), equation 1 reduces to:

$$L_{den,i}' = L_{den,i} + a_{Q,i}(Q_i - \overline{Q_i})L_{den,i} + b_{Q,i}(Q_i - \overline{Q_i})$$

In principle, the parameters a_{Qi} and b_{Qi} can be estimated on the basis of empirical data. Here it is assumed that the parameters a_{Qi} and b_{Qi} do not dependent on the type of noise source, so that they can be written as a_Q and b_Q. Actually, there is very little data available for estimating the parameters. The tentative assignment of values to the parameters is discussed below.

Parameter estimation

The beneficial effect of a quiet side is maximal when the difference between the noise level at the quiet side and most exposed facade is maximal. The beneficial effect will also be higher in a situation with high outdoor noise levels. There are indications that a difference of 15 dB between the highest and lowest noise level, corresponds to a noise reduction at the most exposed façade of 7 dB. Assuming that this beneficial effect occurs at 75 dB and that the beneficial effect of a quiet side starts at 45 dB, then the following two equations determine a_I and b_I:

$a_Q \times 15 \times 75 + b_Q \times 15 = -7$

$a_Q \times 15 \times 45 + b_Q \times 15 = 0$

Solving gives: $a_Q = -0.016$ and $b_Q = 0.70$.

It is assumed that there is a limit to the positive effect of lowering the level at the quiet side and the negative effect of a relatively noisy quiet side. More specifically, it is assumed that the (absolute) effect is maximal when $\left|Q_i - \overline{Q}_i\right| = 20$, and remains at the same level for higher absolute differences. Furthermore, we do not know what happens at extremely high levels (L_{den} > 75 dB(A)), but assume that the effect of a quiet side will not continue to increase.

The effect of the quiet side according to the above assumptions is illustrated in figure 6.3

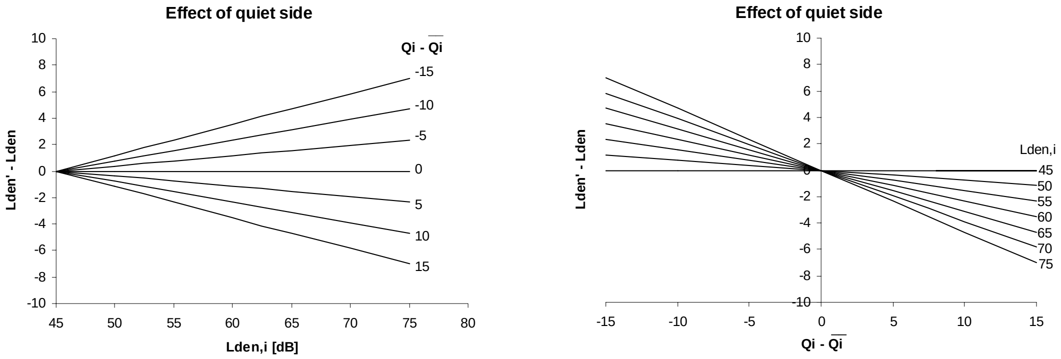

Figure 6.2: Effect of quiet side on the difference between L_{den}' and L_{den} as function of L_{den} (left figure) and as function of the relative quietness at the quiet side (right figure).

Discussion

The beneficial effect of a quiet side will in practice depend on the living room and bedrooms having windows that can be opened at this side of the dwelling, and on the presence of a garden or balcony at the quiet side. It may also depend on the climate.

6.1.3 Ambient noise

When there are quiet places in the vicinity of a dwelling, this also gives some opportunity to escape from the noise in the dwelling. Consequently, it is expected to reduce the annoyance in comparison to situations where there is no such escape. The ambient noise level is defined on the basis of the $L_{outdoor}$ levels, as defined in the subsection on the quiet side but now for points in the vicinity of the dwelling. The ambient noise level *A* can be defined as the lowest 25 percentile of the $L_{outdoor}$ levels within a certain radius around the dwelling, say 200 m.

If we consider only the effect of the ambient noise (suppose the insulation and the quiet side are average), equation 1 reduces to:

$$L_{den,i}' = L_{den,i} + a_{A,i}(A-\overline{A}_i)L_{den,i} + b_{A,i}(A-\overline{A}_i)$$

Parameter estimation

There is no quantitative empirical evidence on the basis of which parameters a_A and b_A (the same for all source types) can be estimated. However, the beneficial effect will be much smaller than the beneficial effect of a quiet side because profit from a quiet side occurs much more frequent. Tentitatively, it is assumed that the beneficial effect is about 25% of the beneficial effect of a quiet side, so that: $a_A = 0.0039$ and $b_A = -0.18$

The effect of ambient noise according the above assumptions is illustrated in figure 6.4.

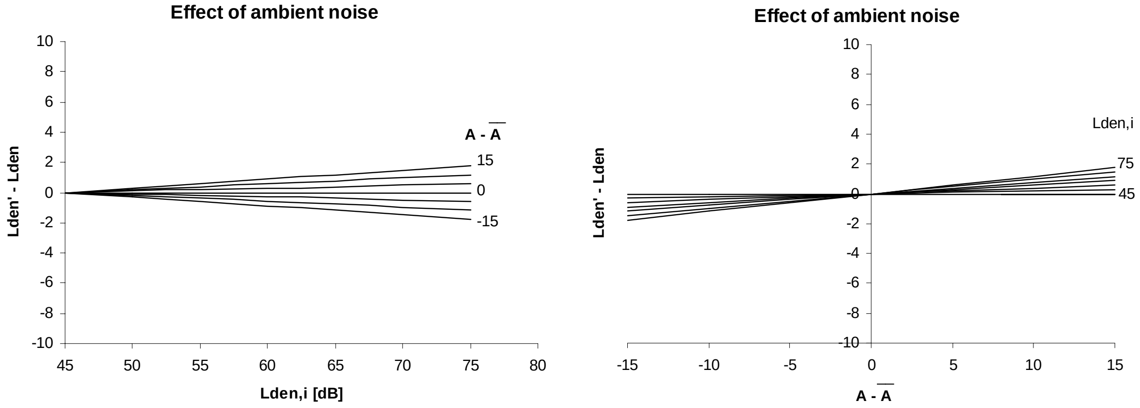

Figure 6.3: Effect of ambient noise level on the difference between *Lden'* and *Lden* as function of *Lden* (left figure) and as function of the relative ambient noise level (right figure).

Discussion

Quiet places in the vicinity of the dwelling can provide a possibility to escape from the noise in the dwelling. The beneficial effect of a relatively quiet surrounding will in practice depend on the quality of these areas in other respects. Parks or other green areas suitable for walking and possibly playing may be particularly beneficial. The value of quiet places in the surrounding may also depend on the climate.

6.2 ADDITIONAL FACTORS AND LNIGHT

Lnight is the metric used to predict sleep disturbance. This section presents an elaboration of this metric which incorporates an important other factor that influences sleep disturbance. The factor taken into account is sound insulation.

If the insulation of the dwelling is higher than average, the indoor noise levels will be lower than average. Therefore, a higher insulation value than average will cause sleep disturbance to be less than expected on the exposure-effect curve. The following metric takes the influence of insulation into account:

$$L_{night,i}' = L_{night,i} + a_{I_b,i}(I_{b,i} - \overline{I}_{b,i})L_{nigth,i} + b_{I_b,i}(I_{b,i} - \overline{I}_{b,i}).$$

Parameter estimation

There is no quantitative empirical evidence on the basis of which parameters a_{Ib} and b_{Ib} (assumed to be the same for all source types) can be estimated, but there are some arguments that indicate possible values. At low noise exposures during the night, people will sleep with windows open, and noise insulation will not affect sleep quality. Therefore, it is assumed that $L_{night,i}$' = $L_{night,i}$ when L_{night} < 40. When night-time noise levels are very high, people will sleep with windows closed, so that they have the full benefit of the extra insulation, but because of the discomfort of having to close the windows, the beneficial effect will not be equal to the extra noise insulation (also see discussion). With the assumption that the maximum effect of 80% of the extra insulation (e.g., 10 dB) is reached at L_{night} = 70, the values for a_{Ib} and b_{Ib} are determined by.

$a_{Ib} \times 10 \times 70 + b_{Ib} \times 10 = -8$
$a_{Ib} \times 10 \times 40 + b_{Ib} \times 10 = 0$
Solving gives: $a_{Ib} = -0.027$ and $b_{Ib} = 1.1$

The effect of sound insulation is illustrated in figure 6.5

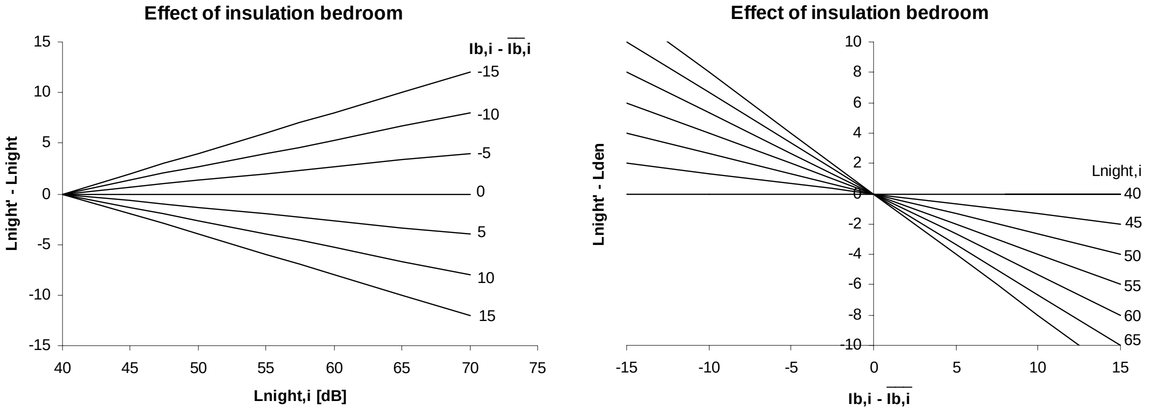

Figure 6.4: Effect of sound insulation of the bedroom on the difference between L_{night}' and L_{night} as function of the night time noise level L_{night} (left figure) and as function of the relative insulation value (right figure).

Discussion

If the ventilation of the bedroom with closed windows is not sufficient, the beneficial effect of noise insulation will be much smaller. A further elaboration of the system would make the beneficial effect of insulation dependent not only on the maximal insulation that can be attained by closing the windows, but also on the quality of the ventilation when the windows are closed.

Noise insulation values for different bedrooms can differ. For example, bedrooms underneath a roof of an older dwelling may have poor insulation compared to bedrooms at lower floors of the same dwelling. In the above procedure, the lowest noise insulation value of a bedroom on the most exposed facade can be used.

7 RATING SYSTEM: STEPWISE PROCEDURE

In this chapter, procedures to calculate the expected percentage highly annoyed, highly sleep disturbed, the number of individuals unacceptably exposed to noise, and the area above 50 dB(A) are described. The procedures can be applied to noise from a single source type and to the total noise. The procedures can be used to calculate the expected effects for the actual situation as well as for scenarios. The procedures below are valid for $L_{den} \leq 75$ dB(A) and $L_{night} \leq 65$ dB(A). It is suggested that the procedure below is applied also to higher exposures because also then reasonable outcomes are expected. The description below is given is given with a view to implementation in software. For a conceptual presentation, we refer to the previous chapters.

7.1 PERCENTAGE HIGHLY ANNOYED

1. Create L_{den} noise maps for all source types.

2. Calculate the percentage highly annoyed for aircraft and for railways:
   $\%HA_{air} = -9.199\times10^{-5} (L_{den} - 42)^3 + 3.932\times10^{-2} (L_{den} - 42)^2 + 0.2939 (L_{den} - 42)$;
   $\%HA_{rail} = 7.239\times10^{-4} (L_{den} - 42)^3 - 7.851\times10^{-3} (L_{den} - 42)^2 + 0.1695 (L_{den} - 42)$.

3. Calculate the equally annoying road traffic levels for aircraft and for railways as follows (*i* is either air or rail):

$$\mathrm{re}(L_{den,i}) = \begin{cases} 46.85 + 168.9\,\mathbf{F}(\%HA_i) - \dfrac{0.8843}{\mathbf{F}(\%HA_i)} & \text{for } L_{den,i} > 42 \\ L_{den,i} & \text{for } L_{den,i} \leq 42 \end{cases}$$

   where

$$\mathbf{F}(x) = \left(-2.374\times10^{-4} + 1.05\times10^{-4}\,x + \sqrt{2\times10^{-7} - 5\times10^{-8}\,x + 1.11\times10^{-8}\,x^2}\right)^{1/3}.$$

4. Calculate a noise map of $L_{outdoor}$:

$$L_{outdoor} = 10\times\lg(10^{0.1\times\mathrm{re}(L_{den,air})} + 10^{0.1\times L_{den,road}} + 10^{\mathrm{re}(L_{den,rail})}).$$

5. Determine for each source $L_{den,i}$ at the most exposed facade for each dwelling.

6. Determine for each source the noise insulation of the dwelling I_i, on the basis of type of dwelling or specific information regarding the dwellings concerned (default: $I_i = \overline{I}_i$).

7. Determine for each dwelling $\min(L_{outdoor})$, the lowest value of $L_{outdoor}$ on a façade of that dwelling, and calculate[2] per dwelling for each source: $Q_i = \mathrm{re}(L_{den,i}) - \min(L_{outdoor})$. (Default $Q_i = \overline{Q}_i$).

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[2] The quietest side may have a higher road equivalent noise level than the road equivalent noise level of the individual source concerned, because the quietest side is defined on the basis of the combined exposure of the various sources. Consequently, $\min(L_{outdoor})$ may exceed $\mathrm{re}(L_{den,i})$ so that Q_i may be negative.

8. Calculate the ambient noise level *A* (25% lowest $L_{outdoor}$ within 200 m) for each dwelling (Source-dependent defaults $A=\overline{A}_i$).

9. Calculate:

$$L_{den,i}' = \begin{cases} L_{den,i} - 0.022 \times \Delta I_i \times L_i + 1.0 \times \Delta I_i & \\ \qquad - 0.016 \times \Delta Q_i \times L_i + 0.70 \times \Delta Q_i & \text{for } L_{den,I} > 45 \\ \qquad + 0.0039 \times \Delta A_i \text{ x } L_i - 0.18 \times \Delta A_i & \\ & \\ L_{den,i} & \text{for } L_{den,I} \le 45 \end{cases}$$

Where:

ΔI_i = minimum [15, maximum (-15, $I_i - \overline{I}_i$)]

ΔQ_i = minimum [20, maximum (-20, $Q_i - \overline{Q}_i$)]

$\Delta A_i = A - \overline{A}_i$, and

$\overline{I}_{air} = 24$; $\overline{I}_{road} = 22$; $\overline{I}_{rail} = 26$;

$\overline{Q}_{air} = 0$; $\overline{Q}_{road} = 7$; $\overline{Q}_{rail} = 10$;

$\overline{A}_{air} = \mathrm{re}(L_{den,air})$; $\overline{A}_{road} = 50$; $\overline{A}_{rail} = 50$;

10. Calculate the percentage highly annoyed for aircraft, road traffic and railways:

$\%HA_{road}' = 9.868 \times 10^{-4}(L_{den,road}' - 42)^3 - 1.436 \times 10^{-2}(L_{den,road}' - 42)^2 + 0.5118\ (L_{den,road}' - 42)$

$\%HA_{rail}' = 7.239 \times 10^{-4}(L_{den,rail}' - 42)^3 - 7.815 \times 10^{-3}(L_{den,\ rail}' - 42)^2 + 0.1695\ (L_{den,\ rail}' - 42)$

$\%HA_{air}' = -9.199 \times 10^{-5}(L_{den,air}' - 42)^3 + 3.932 \times 10^{-2}(L_{den,air}' - 42)^2 + 0.2939\ (L_{den,air}' - 42)$

Note: $\%HA_i' = 0$ if $L_{den,i}' < 42$

11. Calculate the equally annoying road traffic levels for aircraft and for railways as follows:

$$\mathrm{re}(L_{den,i}') = \begin{cases} 46.85 + 168.9\,\mathbf{F}(\%HA_i') - \dfrac{0.8843}{\mathbf{F}(\%HA_i')} & \text{for } L_{den,i}' > 42 \\ & \\ L_{den,i}' & \text{for } L_{den,i}' \le 42 \end{cases}$$

where i = air or rail, and

$$\mathbf{F}(x) = \left(-2.374\times10^{-4} + 1.05\times10^{-4}\,x + \sqrt{2\times10^{-7} - 5\times10^{-8}\,x + 1.11\times10^{-8}\,x^2}\right)^{1/3}$$

12. For evaluation of the combined exposures, calculate for each individual dwelling:

$$L_{den,T}' = 10\times\lg(10^{0.1\times\mathrm{re}(L_{den,air}')} + 10^{0.1\times L_{den,road}'} + 10^{0.1\times\mathrm{re}(L_{den,rail}')})$$

13. Calculate for each individual dwelling the percentage highly annoyed caused by the combined noise:

$\%HA_T' = 9.868\times10^{-4}(L_{den,T}' - 42)^3 - 1.436\times10^{-2}(L_{den,T}' - 42)^2 + 0.5118\ (L_{den,T}' - 42)$

Note: $\%HA_T' = 0$ if $L_{den,T}' < 42$

14. Calculate on the basis of the results of steps 10 and 13 for the community of interest the expected percentage highly annoyed (p_{HA}):

$$p_{HA,i} = \frac{\sum_{dwelling} (\%\,HA_{i,dwelling}' \times n_{dwelling})}{\sum_{dwelling} n_{dwelling}}$$

where *i* = air, road, rail or T, and in which $n_{dwelling}$ is the number of inhabitants of an individual dwelling.

7.2 PERCENTAGE HIGHLY SLEEP DISTURBED

In this section steps to calculate the expected percentage highly sleep disturbed due to a source type *i* and the combined sources are described. These steps can be taken to calculate the expected percentage highly sleep disturbed for the actual situation as well as for scenarios.

1. Create noise maps of $L_{night,\,i}$.

2. Determine the noise level $L_{night,i}$ at the most exposed facade for each dwelling.

3. Determine the noise insulation of the bedroom of each dwelling $I_{b,i}$, on the basis of type of dwelling or specific information on the dwellings concerned. (Default: $I_{b,i} = \overline{I}_{b,i}$).

4. Calculate:

$$L_{night,i}' = \begin{cases} L_{night,i} - 0.027\ \Delta I_i \times L_{night,\,i} + 1.1\ \Delta I_i & \text{for } L_{night,i} > 40 \\ L_{night,i} & \text{for } L_{night,i} \geq 40 \end{cases}$$

   where:

   ΔI_i = minimum [15, maximum (-15, $I_i - \overline{I}_i$)]

   $\overline{I}_{b,air} = 24$; $\overline{I}_{b,road} = 22$; $\overline{I}_{b,rail} = 26$.

5. Calculate for each individual dwelling:
   $\%HSD_{air} = 18.1 - 0.956 \times L_{night,\,air}' + 0.01482 \times L_{night,\,air}'^2$
   $\%HSD_{road} = 20.8 - 1.05 \times L_{night,road}' + 0.01486 \times L_{night,road}'^2$
   $\%HSD_{rail} = 11.3 - 0.55 \times L_{night,\,rail}' + 0.00759 \times L_{night,\,rail}'^2$
   Note: $\%HSD_i = 0$ if $L_{night,\,i}' < 40$

6. Calculate the equally sleep-disturbing road traffic levels per source as follows:

$$\mathrm{re}\left(L_{night,i}'\right) = 35.33 + \sqrt{67.29\ (\%HSD_i) - 151.5}$$

7. For cumulation of night time noise, calculate for each individual dwelling:

$$L_{night,T}' = 10 \times \lg(10^{0.1\times \mathrm{re}(L_{night,air}')} + 10^{0.1\times L_{night,road}'} + 10^{0.1\times \mathrm{re}(L_{night,rail}')})$$

8. Calculate for each individual dwelling:
   $\%HSD_T = 20.8 - 1.05 \times L_{night,\,T}' + 0.01486 \times L_{night,\,T}'^2$
   Note: $\%HSD_T = 0$ if $L_{night,\,T}' < 40$

9. Calculate on the basis of the results of steps 5 and 8 for the community of interest the expected percentage highly sleep disturbed ($p_{HSD,i}$):

$$p_{HSD,i} = \frac{\sum_{dwelling} (\%HSD_{i,dwelling} \times n_{dwelling})}{\sum_{dwelling} n_{dwelling}}$$

   where *i* = air, road, rail or T, and in which $n_{dwelling}$ is the number of inhabitants of an individual dwelling.

7.3 NUMBER OF INDIVIDUALS WITH UNACCEPTABLE NOISE EXPOSURE

1. Calculate re($L_{den,i}$') as in section 7.1 with *i* = air, road, rail or T (result of steps 11 or 12). Note that re($L_{den,i}$') = $L_{den,i}$' when *i* = road or T.

2. Choose a limit *L* above which road traffic noise is considered to be unacceptable and a weighting function. No weighting is obtained by using the constant function which gives the weight above limit *L* as follows:
   $$W(L_{den}) = 1,$$
   while setting $W(L_{den}) = 0$ below the limit. The linear weighting function gives the weight above limit *L* as follows:
   $$W(L_{den}) = 1 + a\,(L_{den} - L),$$
   with a > 0, while setting $W(L_{den}) = 0$ below the limit. The exponential weighting function gives the weight above limit *L* as follows:
   $$W(L_{den}) = 10^{a(L_{den}-L)}$$
   with a > 0, while setting $W(L_{den}) = 0$ below the limit.

3. Calculate for the community of interest, or for small areas as part of hot spot detection the (weighted) number of individuals with unacceptable noise exposure:
   $$n_L = \sum_{dwelling} W(L_{den,T,dwelling}') \times n_{dwelling}$$
   where *i* = air, road, rail or T and in which $n_{dwelling}$ is the number of inhabitants of an individual dwelling.

7.4 PERCENTAGE OF NON-QUIET AREA

In this section, the steps to calculate the indicator $AREA_{50}$, the percentage of area with L_{den} > 50, are described. These steps can be taken for the actual situation as well as for scenarios.

1. Calculate $L_{outdoor}$ as in section 7.1 (result of step 4).

2. Calculate for the area of interest:
   $$AREA_{50} = \frac{\text{Area with } (L_{outdoor} > 50)}{\text{Total area}}$$

REFERENCES

EC. Directive 2002/49/EC of the European Parliament and of the Council, relating to the assessment and management of environmental noise. Official Journal of the European Communities. Brussels: 2002.

EC-WG/2. Position paper on exposure response relationships between transportation noise and annoyance. Luxembourg: 2002.

EC-WG/AEN. Good practice guide for strategic noise mapping and the production of associated data on noise exposure - version 1; Brussels: 2003.

EC-WG/HSEA. Working group on Health and Socio-Economic Aspects. Position Paper on exposure-effect relationships for night time noise. Brussels: 2004.

Guski R. How to forecast community annoyance in planning noisy facilities. Noise & Health 2004, 6 (22) 59-64.

Ising H, Babisch W, and Günther T. Work noise as a risk factor in myocardial infarction. J.Clin.Basic Cardiol 1999, 2 (1) 64-68.

Miedema HME, Vos H. Exposure-response relationships for transportation noise. J.Acoust.Soc. Am. 1998, 104 (6) 3432-3445.

Miedema HME, Vos H. Demographic and attitudinal factors that modify annoyance from transportation noise. J. Acoust. Soc. Am. 1999, 105 (6) 3336-3344.

Miedema HME, Oudshoorn CGM. Annoyance from transportation noise: Relationships with exposure metrics DNL and DENL and their confidence intervals. Environmental Health Perpectives 2001, 109 (4) 409-416.

Miedema HME, Passchier-Vermeer W, Vos H. Elements for position paper on night-time transportation noise and sleep disturbance. TNO Inro report 2002-59. Delft: 2003.

Miedema HME, Vos H. Noise annoyance from stationary sources: Relationships with exposure metric day-evening-night level (DENL) and their confidence intervals. J. Acoust. Soc. Am. 2004, 116 (1) 334-343.

Miedema HME. Relationship between exposure multiple noise sources and noise annoyance. J. Acoust. Soc. Am. 2004, 116 (2) 949 957.

Miedema HME, Vos H. Associations between self-reported sleep disturbance and environmental noise based on reanalyses of pooled data from 24 studies. Beh. Sleep Med. 2007,
5 (1).

Öhrström E, Skånberg A, Svensson H. Effects of Road Traffic Noise and the Benefits of Access to Quietness. Dept of Environmental Medicine, Sahlgrenska Academy at Göteborg University. 2004

Stansfeld SA, Berglund B, Clark C, Lopez-Barrio I, Fischer P, Öhrström E, Haines MM, Head J, Hygge S, Kamp I van, Berry BF. Aircraft and road traffic noise and children's cognition and health: a cross-national study. *Lancet* 2005, 365 (9475)1942-1949.