DELIVERABLE 2.2.1[1]

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2.2	**Refined noise score rating model for residents**
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PP	Restricted to other programme participants (including the Commission Services)	
RE	Restrictec to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for the members of the consortium (including the Commission Services)	

SEVENTH FRAMEWORK PROGRAMME

Nature of Deliverable

R	Report	✓
P	Prototype	
D	Demonstrator	
O	Other	

This deliverable has been quality checked and approved by CityHush Coordinator
Martin Höjer

1 see List of Deliverables, DoW – Annex I to the contract, p.32
(document 233655_CITYHUSH_AnnexI_DoW_2010-01-31_Corrections.pdf - available on the ftp-server)

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0 EXECUTIVE SUMMARY

0.1 OBJECTIVE OF THE DELIVERABLE

The objective is to refine the noise score rating model for residents previously developed within the QCITY project, in which several characteristics of the noise other than the equivalent noise level at the façade were incorporated. So far, the model contained methods for incorporating the effect of ambient noise in the immediate vicinity of the dwelling (quiet façades) and outdoor noise in the neighbourhood, described by the proportion of the area with equivalent sound levels above 50dB(A), as well as the effect of insulation of the dwelling. However, indicators for these effects were not yet adequately based on scientific literature or research. The empirical basis for these indicators is addressed by an inventory of the literature, which is used to evaluate the outdoor environment component in the noise score rating model for residents. In addition, the possibilities are explored to include other aspects, such as the influence of spectrum characteristics and the influence of the rate of occurrence of individual events.

0.2 DESCRIPTION OF THE WORK PERFORMED SINCE THE BEGINNING OF THE PROJECT

An inventory of the literature was made addressing the empirical basis for the influence of outdoor noise in the vicinity of the dwelling, in order to evaluate the outdoor environment component in the noise score rating model for residents. In addition, an overview was made of the information regarding effects of additional characteristics of the noise other than the equivalent noise level, such as the influence of spectrum characteristics and the influence of the rate of occurrence of individual events. As far as possible, a method to incorporate the influence of these characteristics is proposed.

0.3 POTENTIAL IMPACT AND USE[2]

In the context of the EU Environmental Noise Directive, it is important to adequately assess the impact of environmental noise on residents. So far, the assessment of the impact of noise on residents is based solely on façade levels of dwellings as obtained from the noise maps. Therefore, measures directed towards a more quiet outdoor situation, in so far as they are not reflected in façade levels, will not show up in health assessment indicators, nor will measures that influence the frequency spectrum, the indoor levels or the rate of occurrence of individual noise events. Using the refined noise score rating model for residents, the expected effect of environmental noise on residents may be better quantified.

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2 *including the socio-economic impact and the wider societal implications of the project so far*

0.4 PARTNERS INVOLVED AND THEIR CONTRIBUTION

TNO is involved in reviewing the literature on the impact of outdoor environment components on residents and in evaluating and refining the noise score rating model for residents by including characteristics of the noise other than the equivalent noise levels. ACL is responsible for feeding the model with factors that are important from the viewpoint of the CityHush case studies, while ACCON is responsible for the integration of the final validated noise score model in the noise mapping software.

0.5 CONCLUSIONS

Based on current knowledge, the noise score rating model for residents is refined and evaluated. In this rating model, indicators for equivalent noise level at the façade of the dwelling are combined with information about outdoor noise levels in the vicinity of the dwelling, spectrum characteristics (in conjunction with insulation characteristics) and temporal variations in noise levels. This model may be used to predict the overall annoyance response, i.e. the percentage and number of residents that will be expected to be annoyed by noise in a given area.

1 INTRODUCTION

This report describes the results of Work Package 2.2 (WP 2.2) of CityHush. The objective of WP 2.2 was to evaluate and refine the method for predicting annoyance by traffic noise in residents.

The common method for predicting traffic noise annoyance employs an exposure-response function, with noise exposure represented by the day-evening-night noise level at the most-exposed façade of the dwelling (Miedema and Oudshoorn 2001). The refined method developed here takes into account the following additional acoustic factors:

1. quiet façade of the dwelling,
2. quiet areas in the neighborhood of the dwelling,
3. façade insulation of the dwelling,
4. frequency spectrum of the noise, in particular low-frequency components,
5. temporal variations of the noise level, and noise events.

Factors 1, 2, and 3 were included in the method developed within the QCity project (Miedema and Borst 2007). Since the QCity method was *not* based on extensive noise annoyance surveys, only preliminary values were proposed for the numerical parameters of the method.

The QCity method was taken as starting point for the method presented here. The preliminary QCity parameters were compared to results of recent studies of the effects of the additional acoustic factors 1-3. In addition, factor 4 was incorporated in the method, and the possibility to include factor 5 was explored.

2 SETUP OF PREDICTION METHOD

2.1 COMMON METHOD FOR PREDICTING ROAD TRAFFIC NOISE ANNOYANCE

The basis for the refined annoyance prediction method developed here is the exposure-response function (ERF) developed by Miedema and Oudshoorn (2001). Exposure in the ERF is represented by the day-evening-nigh sound level (L_{den}) and response is represented by the (expected) percentage of highly-annoyed people (%HA).

Sections 2.1.1 and 2.1.2 describe the two quantities L_{den} and %HA, while Section 2.1.3 describes the exposure-response functions.

2.1.1 Exposure

The day-evening-night level is defined in the Environmental Noise Directive (END 2002) 2002/49/EC as follows:

$$L_{den} = 10\lg\left(\frac{12}{24}E(L_d) + \frac{4}{24}E(L_e + 5) + \frac{8}{24}E(L_n + 10)\right) \quad (1)$$

with the notation $E(L) = 10^{L/10}$. Here L_d, L_e, and L_n are the A-weighted equivalent sound levels for the day (7-19h), evening (19-23h), and night (23-7h), respectively. The penalties for the evening (5 dB) and the night (10 dB) represent the fact that noise is rated more severely during the evening and the night than during the day.

According to the END, major EU cities have to produce urban distributions of the L_{den} façade level, *i.e.* the L_{den} level at the most-exposed façade of a dwelling (excluding the façade reflection, and calculated at a height of 4 m). The distributions are collected on the website http://noise.eionet.europa.eu/ of the European Environment Agency, and provide a ‘picture’ of current noise exposure in European cities.

2.1.2 Annoyance

The percentage of highly-annoyed people, %HA, is an indicator of the prevalence of annoyance by road traffic noise. Annoyance at population level is commonly assessed by means of questionnaire surveys, with a question about road traffic noise annoyance in the situation at home. People are asked to indicate the degree of annoyance on a numerical scale, such as an 11-point scale (0-10) or a five-point scale (1-5). After converting the results to a 0-100 scale, cut-off values of 50 and 72 are used to determine the percentages of people annoyed (%A) and highly-annoyed (%HA), respectively. Here %HA is chosen as an indicator, as this is the most widely used indicator, but the approach for %A is analogous.

2.1.3 Exposure-response function

An EU position paper on exposure-response relations for transportation noise annoyance (EU 2002) presents ERF's for annoyance by aircraft noise, road traffic noise, and railway noise. The ERF's are based on statistical analyses of 54 noise annoyance studies from Europe, North America, and Australia (Miedema and Oudshoorn 2001). The ERF for road traffic noise is:

$$\%HA = 9.868 \cdot 10^{-4}(L_{den} - 42)^3 - 1.436 \cdot 10^{-2}(L_{den} - 42)^2 + 0.5118(L_{den} - 42)\,. \qquad (2)$$

The ERF is shown graphically in figure 2.1. For comparison, also the ERF's for aircraft noise and railway noise are included in the figure. For road traffic noise, %HA is zero for levels of 42 dB and lower, and increases with increasing level to 37% at 75 dB. Miedema and Oudshoorn have further shown that the 95% confidence intervals around the ERF's are rather small, indicating the precision with which the average curves are estimated, although there are considerable variations between individuals and between studies.

Many dwellings are exposed to a combination of road traffic noise, railway noise, and aircraft noise. For these dwellings the annoyance can be calculated with a method developed by Miedema (Miedema 2004, Miedema and Borst 2007). The basic idea of the method is that the levels of aircraft noise and railway noise are first converted to 'road-equivalent' levels (levels of road traffic noise inducing equal annoyance) and next the levels are summed (logarithmically).

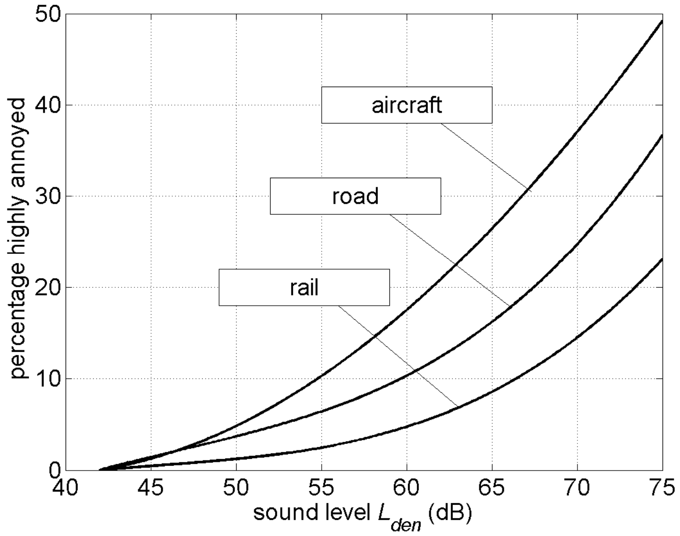

Figure 2.1 Exposure-response functions for annoyance by aircraft noise, road traffic noise, and railway noise (Miedema and Oudshoorn 2001).

It is important to note that the ERF's represent the expected annoyance in the situation *in and around the house* (Miedema and Vos 1998). Although there are variations in the precise phrasing of the annoyance question used in the 54 studies, many studies used the expression 'annoyance *at home*' in the question. People may have different interpretations of '*at home*', but many people will consider not only the house itself but also locations near the house such as a garden in the response to the question.

The fact that the ERF represents expected annoyance in and around the house is important for the choice of additional acoustic indicators of the refined model presented in this report. Two of these indicators are partly related to noise perception at locations around the house:

i) the façade level at the *least-exposed* façade (quiet façade),

ii) the sound level in quiet areas near the house (ambient noise level).

The first indicator may account for the beneficial effect of a quiet façade on traffic noise annoyance, for example due to reduced noise levels in a quiet backyard or a quiet bedroom. The second indicator may account for the effect of nearby quiet areas such as parks, where people may 'escape' from the noise directly near the house or in the house.

2.2 ADDITIONAL ACOUSTICAL FACTORS : THE QCITY MODEL

The refined method presented here takes into account the following additional acoustic factors:

1. quiet façade of the dwelling,
2. quiet areas in the neighborhood of the dwelling,
3. façade insulation of the dwelling,
4. frequency spectrum of the noise, in particular low-frequency components,
5. temporal variations of the noise level, and noise events.

Factors 1-3 were included in the QCity noise score rating model (Miedema and Borst 2007). Factor 4 is taken into account through the frequency dependence of façade insulation, as described in Chapter 5. So for factors 1-4 the QCity model serves as a basis.

This section in short describes the setup of the QCity model, extended with factors 4 and 5. In the following chapters the values of the numerical parameters of the model are described, both the preliminary values proposed in QCity, and their evaluation based on recent noise annoyance studies.

The QCity model starts from the assumption that the exposure-response function for annoyance is valid for the 'average' situation, with average values for the factors 1, 2, and 3. Here 'average' refers to an average over the populations of the noise annoyance surveys employed for the derivation of the exposure-response function (ERF). Local deviations from the average values correspond to local deviations from the expected annoyance according to the ERF. To calculate the local annoyance deviations, an adjusted façade level is defined:

$$L_{den}' = L_{den} + \Delta L_I + \Delta L_Q + \Delta L_A \quad (3)$$

with

$$\Delta L_I = a_I (I - I_{av}) L_{den} + b_I (I - I_{av}) \quad (3a)$$

$$\Delta L_Q = a_Q (Q - Q_{av}) L_{den} + b_Q (Q - Q_{av}) \quad (3b)$$

$$\Delta L_A = a_A (A - A_{av}) L_{den} + b_A (A - A_{av}) \quad (3c)$$

and

I = façade insulation (outdoor level minus indoor level),

Q = level at most-exposed facade minus level at least-exposed facade,

A = ambient noise level within a radius of 200 m around the dwelling.

The quantities ΔL_I, ΔL_Q, and ΔL_A are correction terms for local deviations of I, Q, and A from the average values I_{av}, Q_{av}, and A_{av}, respectively, and a_I, b_I, a_Q, b_Q, a_A, and b_A are numerical parameters. For simplicity, only one type of environmental noise (road traffic, railway, or aircraft noise) is considered. For situations with combined exposure, the reader is referred to QCity (Miedema and Borst 2007).

The adjusted level L_{den}' is considered as an equivalent level at the most-exposed façade, and substitution of L_{den}' into the exposure-response function (2) yields an estimate of the percentage highly-annoyed people in a situation with acoustic indicators I, Q, and A.

The three correction terms on the right-hand-side of Eq. (3) are just parameter representations of the effects of the three acoustical indicators on annoyance. In principle, there are two adjustable parameters for each correction term (a and b). In practice, however, the quantities I_{av}, Q_{av}, and A_{av} are also not known. Moreover, I_{av}, Q_{av}, and A_{av} may not even be constants, but functions of L_{den}. For example, Q_{av} increases in general with increasing L_{den}. In the following chapters the problem of the values of the parameters in Eq. (3) is addressed.

Finally, the additional acoustical indicators 4 and 5 are considered.

Indicator 5, temporal fluctuations of the noise level, and the rate of occurrence of noise events, is included because temporal fluctuations are not represented by the time-averaged sound level L_{den}. Fluctuations and variations at various time scales may play a role, from minutes to months. This topic is discussed in Chapter 6. However, it turns out that current knowledge about the effects of temporal variations is not sufficient for developing a correction term similar to the correction terms in Eq. (3).

3 QUIET FACADE

An element of the European policy for reduction and control of the harmful effects of traffic noise is the protection of quiet areas and quiet facades of dwellings (European Commission 2002). The idea is that quiet facades and quiet areas reduce annoyance by traffic noise. A quiet façade allows people to benefit from a quiet backyard or a quiet bedroom. Figure 3.1 illustrates the case of a quiet façade (quiet side).

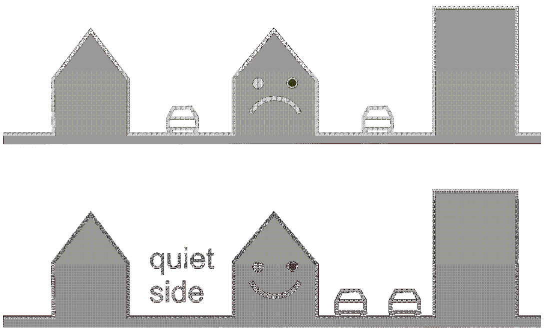

Figure 3.1 Illustration of the creation of a quiet side of a house in a city. Top: with traffic flow on both sides of the house, inhabitants are annoyed. Bottom: with all traffic on one side of the house, inhabitants have access to a quiet side and may be less annoyed.

Two points should be mentioned. First, as shown in the figure, 'moving' all traffic to one side of the house creates more traffic noise on this side, and a question is whether this is outweighed by the beneficial effect of the quiet side. Second, the exposure-response relations are based on populations that live in cities that to some extent already have quiet facades, so the quiet-façade correction (3b) is zero for this average situation, or reference situation ($Q = Q_{av}$). Application of the quiet-façade correction therefore only corresponds to a local refinement of the annoyance prediction, or a refinement due to measures aimed at the creation or protection of quiet facades (an analogous argument holds for the façade-insulation correction 3a and the ambient-noise correction 3c).

This chapter presents the approach proposed in QCity for façade insulation, with preliminary values for the numerical coefficients (Section 3.1). Next, relevant recent studies into the effects of quiet façades are discussed (Section 3.2). In Section 3.3 conclusions are presented with respect to the preliminary QCity approach.

3.1 PRELIMINARY APPROACH

In QCity the preliminary values

$$a_Q = -0.0156 \text{ and } b_Q = 0.7 \tag{7}$$

of the coefficients in Eq. (3b) have been proposed. These values were derived from the assumption that a value of $Q - Q_{av}$ = 15 dB at outdoor level 75 dB would correspond to a correction term of -7 dB ($\Delta L_Q = -7$ for L_{den} = 75 and $Q - Q_{av}$ = 15), while the correction term would be zero at outdoor level 45 dB. The resulting correction term as a function of L_{den} and $Q - Q_{av}$ is shown graphically in Figure 4.1. The average value Q_{av} was not specified in QCity.

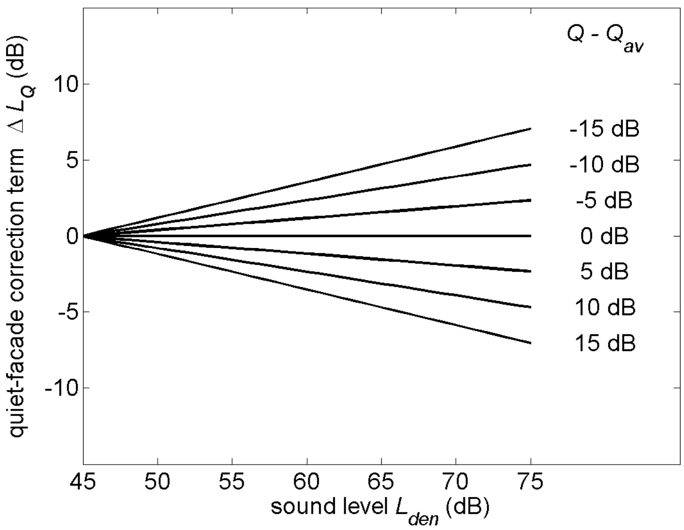

Figure 3.1 Quiet-façade insulation correction term (3b) calculated with preliminary values given in Eq. (7) for different values of $Q - Q_{av}$.

3.2 Recent studies

Öhrström et al (2006) have reported a study into the benefit of access to a quiet façade. This study focused on residential areas in Stockholm and Gothenburg, with a considerable percentage (50%) of dwellings with a quiet façade (10-20 dB lower than most exposed façade). Noise levels were determined by a combination of measurement and calculation based on traffic data and geometrical data. Socio-acoustic surveys were conducted in the period 2000-2002. Out of 1 625 individuals between 18 and 75 years of age, 956 participated (59% response rate) and 458 had access to a "quiet" side of their dwelling while 498 had no such access.

The results of the study indicated that access to a quiet façade reduces disturbances considerably. It was found that the effect corresponds to a reduction in sound levels of 5 dB at the most-exposed façade (L_{Aeq24h}).

Support for the result of Öhrström et al (2006) comes from a Norwegian study reported by Amundsen et al (2011). This study yields a beneficial effect of 6 dB (equivalent outdoor level reduction) due to 'having the bedroom on the quiet facade'. In other words, the difference in annoyance between 'having the bedroom on the least-exposed façade' and 'having the bedroom on the most-exposed façade' corresponds to an exposure difference of 6 dB.

A recent population study into the beneficial effect of a quiet facade was performed by de Kluizenaar et al (2010). The study was performed in an urban area in the Netherlands, and 18973 persons participated in the study. Noise levels at the most and least exposed facades were calculated. The participants provided responses to a number of questions, including a question about annoyance by traffic noise. Results of the study indicate that, taking into account possible confounders, residents may benefit from a quiet façade of the dwelling. The effect in terms of L_{den} found was of the order of 2 dB.

While the above three studies did find a beneficial effect of a quiet façade, a recent study by Botteldooren et al (2011) gave a different result. It was found that the noise level at the quiet façade had no significant effect on traffic noise annoyance (in and around the house, over the last 12 months). In contrast, it did have a significant effect on the perceived quality of the living environment. These results are based on large surveys of the quality of the living environment in Flanders (Belgium), which are conducted every 3 years. Three databases with 3 year intervals (13000 participants in total) were available for the study. Another interesting result from this study is that noise exposure during trips has a significant effect for noise annoyance in and around the house and also for quality of the living environment. The noise exposure during trips was calculated for trips within a 300 m distance from the house, measured along the most probable routes for leaving the dwelling (this result is relevant for the effect of ambient noise, discussed in the next chapter).

3.3 Conclusion

The results of the studies described in the previous section have not yet been interpreted in terms of adjusted values for the parameters a_Q and b_Q in Equation (3c). However, most of the studies give a considerable beneficial effect of quiet facades, in the same order as the proposed values in QCity. Therefore, the preliminary QCity values given in Equation (7) can be used for the model presented here.

A European project called QSIDE (2010-2013, www.qside.eu) aims at the derivation of values for the parameters a_Q and b_Q from re-analyses of available noise annoyance studies. The Dutch, Belgian and Swedish authors of the studies described in the previous section participate in this project.

In addition to the values of a_Q and b_Q, a value is required for the average value Q_{av}. In principle, Q_{av} may even be a function of L_{den}, since dwellings with high noise exposure at the most-exposed façade are expected to have larger values of Q than dwellings with low noise exposure at the most exposed façade, on the average (De Kluizenaar 2010). However, this relation is as yet unquantified. Ideally, one would derive the value of Q_{av} for the population on which the exposure-response relation for annoyance was based. However, since information on quiet façades is missing for most of the studies in the original database, this is not a feasible solution. As a preliminary practical choice one may use a typical value of 10 dB for Q_{av}. Further consideration of the parameter Q_{av} will be part of the project QSIDE mentioned above.

4 AMBIENT NOISE

In addition to an effect of quiet façades, quiet places in the vicinity of the dwelling can provide a possibility to escape and restore from the noise in the dwelling. Therefore, relative quietness in the direct vicinity of the dwelling is expected to reduce the annoyance in comparison to situations where there is no such escape.

In QCity it was proposed to use quantity A to represent ambient noise around the house:

A = lowest 25 percentile of $L_{outdoor}$ within a radius of 200 m around the dwelling,

with $L_{outdoor}$ being the cumulated outdoor noise level in dB(A).

However, other choices are also possible. The beneficial effect of a relatively quiet surrounding will in practice depend on the quality of these areas in other respects, with parks or other green areas suitable for walking being particularly beneficial. Alternatively, one may choose to assign higher weights to locations visited more frequently by people (such as travel routes) and lower weights to locations visited less frequently. In other words, rather than using a uniform average over a circular area with a radius of 200 m around the dwelling, one may use a *weighted* average that assigns higher weights to specific locations in the area. Also the choice of the radius of 200 m may be modified in principle if another value proves more appropriate.

4.1 PRELIMINARY APPROACH

In QCity the preliminary values

$$a_A = -0.0039 \text{ and } b_A = 0.175 \qquad (8)$$

of the coefficients in Eq. (3c) have been proposed. These values were derived from the assumption that the beneficial effect of low ambient noise is about 25% of the beneficial effect of a quiet façade. The resulting correction term as a function of L_{den} and $A - A_{av}$ is shown graphically in Figure 4.1. The average value A_{av} was not specified in QCity.

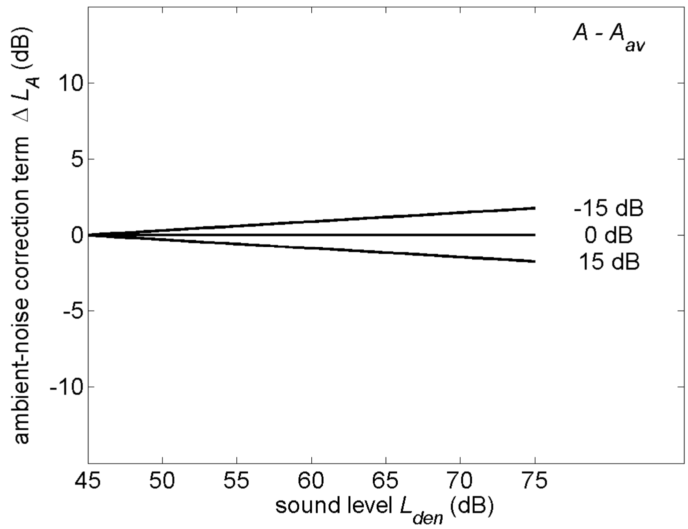

Figure 4.1 Ambient noise correction term (3c) calculated with preliminary values given in Eq. (8) for different values of $A - A_{av}$. For clarity, the scaling is the same as in Figure 3.1.

4.2 SOME RELEVANT STUDIES

In a study by Fields (1998) situations with target noise ('foreground noise') and ambient noise ('background noise') were investigated. It was found that ambient noise does influence the loudness of target noise, but that the effect on annoyance by target noise was negligible. However, this study addressed the influence of ambient noise from a different noise source than the target noise, both assessed for the location of the dwelling. This differs from the definition of ambient noise in a certain radius around the dwelling, the influence of which is addressed here.

Gidlöf-Gunnarson and Öhrström (2007) have reported a study into the potential role of perceived availability to nearby green areas. The effect of nearby green areas on annoyance at home and annoyance outdoors was investigated. The study was performed in residential areas in Stockholm and Gothenburg. Noise levels were determined by a combination of measurement and calculation based on traffic data and geometrical data. Socio-acoustic surveys were conducted in the period 2000-2002. Out of 1 625 individuals between 18 and 75 years of age, 956 participated (59% response rate). Out of the 956 participants, a restricted set of 500 residents was selected that was exposed to high levels of road traffic noise (L_{Aeq24h} = 60 – 68 dB at the most-exposed façade of the dwelling).

Participants indicated degree of annoyance by road traffic noise on a scale from 0 to 10. Based on self-reported perceived availability to green areas, two groups were formed: residents with 'poorer' availability to green areas (356 residents) and residents with 'better' availability to green areas (146 residents).

The results indicate that the degree of perceived availability of nearby green areas affected the residents' responses to road traffic noise. This is shown graphically in Figure 4.2. The figure shows that perceived availability of nearby green areas corresponds to a 30% reduction of the noise annoyance score, both at home and outdoors around the home. In addition, a distinction was made between residents with access to a quiet façade and residents without access to a quiet façade at home. Both categories of residents were found to benefit from nearby green areas. However, since the availability of access to green areas was detected on the basis of self-report, it was not possible to quantify the effect on annoyance expressed in equivalent dB changes.

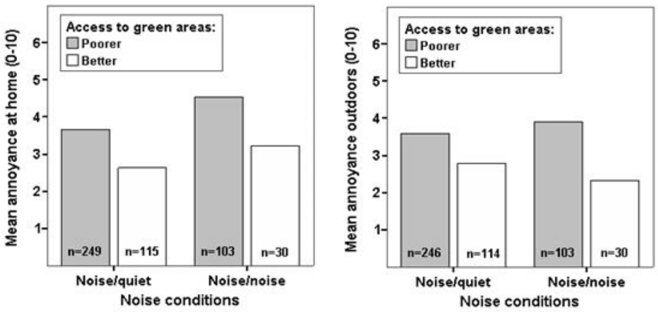

Figure 4.2 Illustration of the reduction of annoyance due to access to green quiet areas, for residents with (Noise/quiet) and without (Noise/noise) access to a quiet façade, both for annoyance at home (left) and for annoyance outdoor (right).

A study by Klaeboe et al (2005) showed that an adverse neighbourhood soundscape has a substantial impact on residential noise annoyance. The degree of adverse neighbourhood soundscape was defined by the difference in dB between the highest equivalent noise level encountered in the immediate vicinity of the dwelling (within a radius of 75 m) and the noise level at the most exposed façade. It was found that an increase in the degree of adverse neighbourhood soundscape of approximately 2 dB increases the probability that a resident reports a higher degree of annoyance by the same amount as an increase of 1 dB in the façade noise level. This trade-off factor was subsequently incorporated in a method for context sensitive noise mapping (Klaeboe et al 2006). In a follow-up analysis (Klaeboe 2007), also the effect of the degree of quiet neighbourhood soundscape was explored, defined as the difference between the minimum equivalent noise level encountered in the immediate vicinity of the dwelling (within a radius of 75 m) and the noise level at the most exposed façade. The correlation between the indicators for adverse and quiet neighbourhood soundscape was low (around 0.10), suggesting that there is no systematic relationship between the presence or absence of noisy and quiet areas for a given dwelling. The degree of adverse neighbourhood soundscape induced the same increase in annoyance as found before, also after adjusting for possible absence of quiet areas, while the expected benefit of a quiet neighbourhood soundscape was not found.

Finally, the study of Botteldooren et al (2011) described already in the previous chapter indicated that noise exposure during trips near the house has a significant effect on traffic noise annoyance (and even more so on perceived quality of the living environment). The noise exposure during trips was calculated for trips within a 300 m distance from the house, measured along the most probable routes for leaving the dwelling. This result would imply that it may be better to use for ambient noise level *A* in Equation (3c) a weighted average with high weights for common travel routes rather than a uniform average over a circular area with a radius of 200 m around the dwelling. Also, the results suggest that while ambient noise may have an impact on annoyance at home, it may be even more relevant for perceived quality of the living environment.

4.3 CONCLUSION

Recent studies provide support that the level of ambient noise in a certain radiance around the dwelling indeed influences annoyance by traffic noise at home. However, the results of the studies described in the previous section could not yet be interpreted in terms of adjusted values for the parameters a_A and b_A in Equation (3c). The European project QSIDE mentioned in the previous chapter aims at the derivation of estimated values for the parameters a_A and b_A from re-analyses of available noise annoyance studies. Given the current uncertainty, a conservative approach may be taken by following the proposed (low) values in QCity.

In addition to the values of a_A and b_A, a value is required for the average value A_{av}. Again, one would ideally derive the value of A_{av} for the population on which the exposure-response relation for annoyance was based. This appears not to be feasable, since the information on ambient noise in these studies is very limited.

Furthermore, the definition of quantity *A* is still under discussion. Different studies used different values for the radius around the dwelling, and different indicators for either the noise or quietness in the defined area. This problem will be investigated also in the project QSIDE.

5 FACADE INSULATION AND NOISE FREQUENCY SPECTRUM

Two different origins of local deviations of façade insulation I from the average value I_{av} are distinguished here:

- construction of dwellings,
- frequency spectrum of noise.

The role of the spectrum of the noise is related to the frequency dependence of façade insulation. Façade insulation is lower at low frequency than at high frequency. This leads to an *indirect* correction for the spectrum, i.e. a correction via façade insulation.

In addition, there may be a *direct* effect of the spectrum on annoyance. For example, low-frequency may be more annoying than mid-frequency or high-frequency noise (at constant A-weighted sound level). Studies into this direct effect of the spectrum have been reported in the literature, but the results are not sufficiently clear (yet) to provide support for such a direct effect.

This chapter first describes the approach proposed in QCity for façade insulation, with preliminary values for the numerical coefficients (Section 5.1). Next, the relevant literature about façade insulation (Section 5.2) and the direct effect of the spectrum on noise annoyance (Section 5.3) are discussed. In Section 5.4 numerical examples of the indirect effect of the spectrum via façade insulation are presented. In Section 5.5 conclusions are presented with respect to the preliminary QCity approach.

5.1 PRELIMINARY APPROACH

In QCity the preliminary values

$$a_I = -0.0222 \text{ and } b_I = 1 \tag{4}$$

of the coefficients in Eq. (3a) have been proposed. These values were derived from the assumption that an extra noise insulation of 15 dB at outdoor level 75 dB would correspond to a correction term of -10 dB ($\Delta L_I = -10$ for L_{den} = 75 and $I - I_{av}$ = 15), while the correction term would be zero at outdoor level 45 dB. The resulting correction term as a function of L_{den} and $I - I_{av}$ is shown graphically in Fig. 5.1. The average value I_{av} was not specified in QCity.

The maximum effect of 10 dB for 15 dB extra insulation occurs at 75 dB. In other words, the (maximum) 'efficiency' of 15 dB extra insulation is 67% (10 dB is 67% of 15 dB), which is less than 100% because the annoyance is partly induced by noise exposure experienced around the house rather than in the house. Here the efficiency is defined as $|\Delta L_I| / |I - I_{av}|$. In the next section the efficiency of 67% is compared with results of a recent façade insulation study.

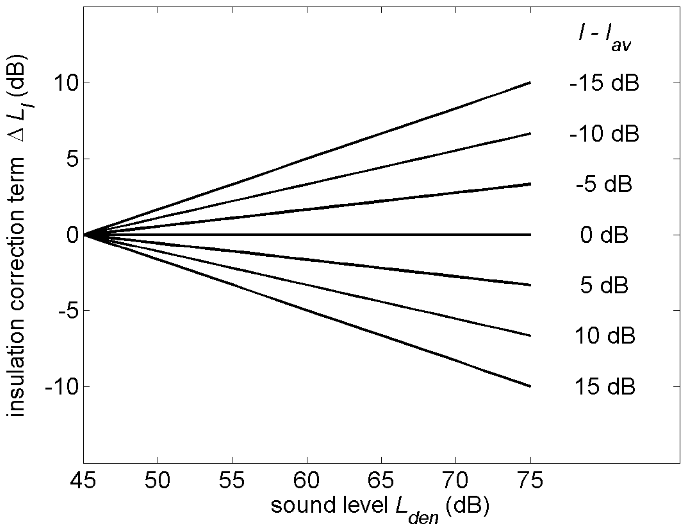

Figure 5.1 Façade insulation correction term (3a) calculated with preliminary values given in Eq. (4) for different values of $I - I_{av}$. For clarity, the scaling is the same as in Figures 3.1 and 4.1.

5.2 FAÇADE INSULATION

Façade insulation is in general defined as the difference between an outdoor level and an indoor level. Different versions exist of the exact definition, but here it is assumed that the outdoor level is the façade level L_{den}, which represents incident sound (not including the façade reflection). The indoor level is often normalized to a reverberation time of 0.5 s, but this normalization is ignored here.

Figure 5.2 shows the façade insulation spectrum used for calculations presented later in this chapter (Vos 2010). The numerical values are given in Table 5.1. This spectrum should only be considered as a typical representative example, as insulation spectra in practice show large variations. The increase of façade insulation with frequency is a typical characteristic of façade insulation spectra.

The strong frequency dependence of façade insulation can be understood from the expression for the transmission loss R for a solid wall (and normal sound wave incidence):

$$R(\omega) = 10\lg\left[1 + \left(\frac{\omega m}{2Z}\right)^2\right] \tag{4}$$

which is commonly referred to as the mass law for sound transmission [Pierce 1991, Fahy 2007, Dowling 1983]. Here, m is the mass of the wall per unit area, Z is the impedance of air, and ω is the angular frequency of the transmitted sound wave. For $\omega >> 2Z/m$ the transmission loss increases by 6 dB per octave. For example, for m = 50 kg/m^2, the expression yields a transmission loss of 12 dB at 10 Hz and about 50 dB at 1 kHz. Sound transmission through the façade of a house depends not only on the walls, but also on various structural elements and openings in the façade (air ventilation, windows, sealing), which limit the façade insulation spectrum at high frequency. Consequently, façade insulation spectra in practice show large variations [Vermeir 2004, Haberl 2005, Tadeu 2001, Vos 2001, Meloni 1995, Yaniv 1982], depending on the wide variety of façade structures of houses. Moreover, opening and closing of windows of houses plays an important role in the variations of façade insulation.

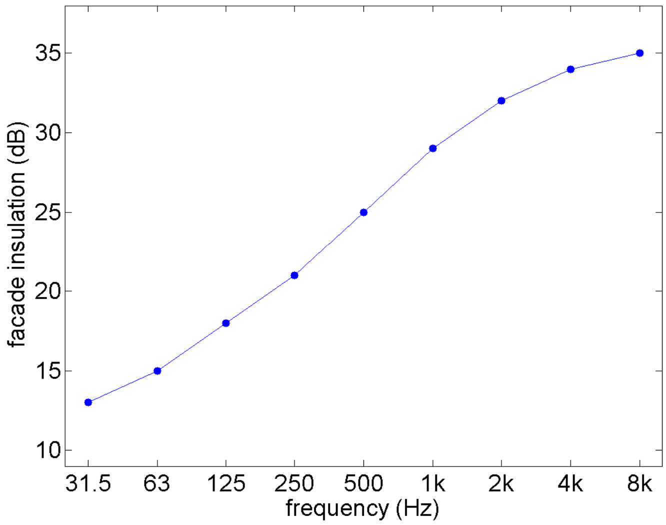

Figure 5.2 Octave band spectrum of façade insulation. The numerical values are given in Table 5.1.

Table 5.1. Values of façade insulation *I* in Figure 5.2, as a function of octave band frequency *f*.

f (Hz)	31.5	63	125	250	500	1k	2k	4k	8k
I (dB)	13	15	18	21	25	29	32	34	35

Recently, a large-scale study of the effect of facade insulation on road traffic noise annoyance in Norway was published [Amundsen 2011]. The study is linked to a large-scale façade insulation improvement to meet Norwegian noise regulations, with the intention to reduce indoor levels to about 36 dB and to ensure that ventilation is satisfactory (active ventilation) without having to open windows. The objective was to improve the situation (before 2005) for all dwellings with indoor levels of 42 dB or higher. The before-study had 637 respondents and was performed in 2003-2004. The after-study had 415 respondents and was performed in 2005 after the insulation measures had been implemented. Of the 415 respondents, 161 had 'received' the insulation measure (target group) and 254 had not (control group). The outdoor noise levels of respondents were high (61-78 dB). Noise exposure was represented by $L_{Aeq,24h}$, the 24h equivalent sound level. This quantity was assessed both outside and inside (with closed windows) the most-exposed façade of the dwelling.

Table 5.2. Effect of insulation on indoor and outdoor L_{Aeq} levels and annoyance inside the dwelling (Amundsen 2011).

Insulation		$L_{Aeq,24h}$		Annoyed by noise when inside dwelling (%)				
		indoor	outdoor	Extremely	Very	Moderately	Slightly	Not annoyed
Target group	Before	43	71	10.8	31.6	26.6	17.7	13.3
	After	36	71	2.0	13.5	25.2	33.3	25.9
Control group	Before	39	69	5.2	18.3	28.2	25.4	23.0
	After	39	69	6.8	22.0	21.5	27.3	22.4

The insulation resulted in a substantial and significant reduction in noise annoyance, as shown in the table above. In the target group, the percentage highly annoyed (extremely + very) dropped from 42% before to 16% after the insulation measure. The corresponding percentages in the control group are 24% and 29%. It was found that the effect on annoyance of 'Receiving the insulation noise measure' is equivalent to that of a reduction of the outdoor noise level by 7 dB. Since the actual average insulation was also 7 dB, the authors conclude that the annoyance reduction due to the insulation measure may be deduced from the exposure-response relationship based on the results of the before-study, by looking at the expected response at façade levels that are reduced by 7 dB. Indeed, the exposure-response curve given in Figure 5.3 for highly annoyed (very + extremely) yields 41% at 43 dB and 21% at 36 dB, and these percentages approximately agree with the values 42% and 16% indicated above.

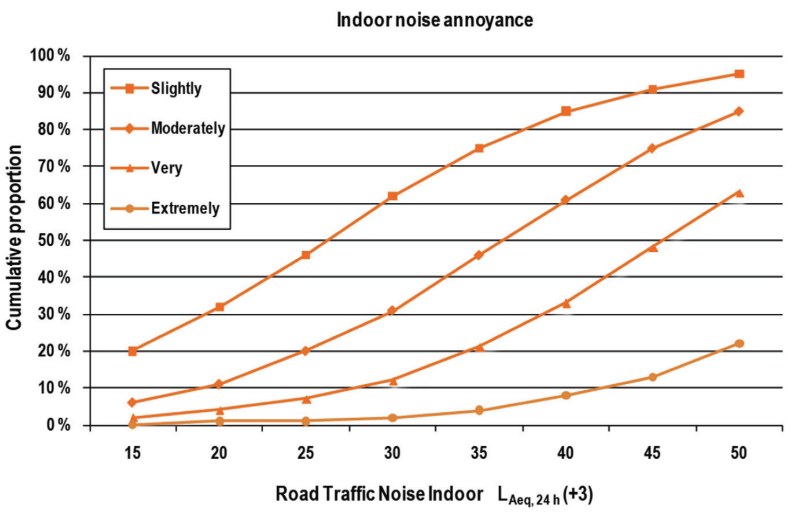

Figure 5.3 Cumulative proportions (in %) of indoor noise annoyance based on the results of the before-study.

Thus, the Norwegian study provides evidence for the effect of insulation described in the previous section. The study does not provide support for the functional form of the effect as assumed in Q-City, but rather yields a constant value of 100% for the façade insulation efficiency (introduced in the previous section). The efficiency of 100% should be considered as an average over the exposure interval considered: 61 – 78 dB(A). For comparison, QCity assumed an efficiency of 67% at 75 dB(A). Still, this could be in line with each other, since the Norwegian study focused on annoyance *inside* the dwelling, while the model developed here aims at annoyance 'in and around the house.' The effect of insulation on annoyance 'in and around the house' is expected to be smaller than the effect on annoyance inside the dwelling. Furthermore, the authors of the Norwegian article indicate that their calculated 7 dB insulation may have been an underestimation (by 3 dB). If the true value would be 10 dB, this implies a 70% effect instead of a 100% effect. On the other hand, the calculated insulation applies to the situation with closed windows, while in practice windows will be open part of the time.

5.3 LOW-FREQUENCY NOISE

As indicated before, an *indirect* effect of the spectrum on annoyance is included in the model, i.e. a correction via façade insulation. In addition, there may be a *direct* effect of the spectrum. In this section the direct effect is discussed, and in the next section the indirect effect is discussed. More information on the analysis presented here can be found in recent publications [Salomons 2011, Lentzen 2011].

An essential role in the direct effect is played by the A-weighting curve, since L_{den} is an A-weighted sound level. The A-weighting curve for rating noise was originally derived from an equal-loudness contour for pure tones, the 40 phon Fletcher-Munson curve [Fletcher 1933], so equal A-weighted sound levels would approximately correspond to equal loudness. There have been several revisions of the equal-loudness contours for pure tones [ISO 1987, ISO 2003, Suzuki 2004]. Further, calculation methods have been developed for broadband noise, such as the ANSI standard (ANSI 2007), which show that the shape of the spectrum has a large effect on the loudness. If one considers loudness level variations at constant A-weighted sound level it becomes clear that the A-weighted sound level is only a limited representation of direct noise perception. For example, several authors have reported that A-weighting underestimates loudness at low frequency (LF), and therefore would be inappropriate for LF environmental noise control [Leventhall 2003, Berglund 1996, Hodgdon 2007, Nilsson 2007]. However, a clear picture of the relation between loudness and annoyance by LF noise does not emerge from the various studies on annoyance caused by LF noise [Persson 1988, Bengtsson 2004, Vos 2010, Møller 1987, Inukai 2000, Persson Waye 2001, Poulsen 2007]. A complicating factor is that annoyance depends also on other acoustic characteristics than loudness. For example, tonal noise is found to be more annoying than broadband noise at the same sound level [Hellman 1984, Ryherd 2008, Bray 2010]. Since LF noise in particular often has tonal components (for example, noise from 50 Hz transformers (van den Berg 1998), tonality and LF character may interfere.

In a recent laboratory study of LF noise annoyance [Vos 2010] indications were found that the A-weighted equivalent sound level *at the ear* is a good predictor for LF noise annoyance. This suggests that the direct effect of the spectrum on annoyance is small, and that the main effect to take into account is the indirect effect via façade insulation.

5.4 VARIATION OF FAÇADE INSULATION WITH NOISE SPECTRUM

Heavy vehicles such as trucks cause noise with relatively strong low-frequency components. The low-frequency components are assumed to cause enhanced annoyance because the transmission loss of dwelling facades (façade insulation) is lower for LF noise than for average traffic noise. Consequently, if the proportion of heavy vehicles in an urban street is high, annoyance at a given noise level will be expected to be higher than in streets with lower proportions of heavy vehicles.

Equation (3a) for the façade-insulation correction term requires a value for the broadband façade insulation I. This value is calculated by combining the frequency-dependent insulation values I_j in Table 5.1 with a sound spectrum of traffic noise:

$$I = 10\lg\left(\sum_{j=1}^{9} 10^{L_{A,j}/10}\right) - 10\lg\left(\sum_{j=1}^{9} 10^{(L_{A,j}-I_j)/10}\right) \tag{5}$$

Here $L_{A,j}$ is the A-weighed sound level in octave band j (j = 1 - 9 for 31 – 8000 Hz). It should be noted that the result is independent from absolute sound levels. Only the shape of the spectrum is important.

In Sections 5.4.1 and 5.4.2 numerical examples are presented of practical values of the broadband façade insulation calculated with Equation (5).

5.4.1 Road traffic noise calculated with the HARMONOISE/IMAGINE model

In this section values of the insulation I are calculated with Eq. (5) in combination with the IMAGINE road traffic noise emission model [IMAGINE, 2007]. As an approximation, the emission spectrum $L_{WA,j}$ for the sound spectrum $L_{A,j}$ is used, neglecting the propagation attenuation. This is a good approximation in particular for directly-exposed dwellings. For dwellings shielded by other buildings or noise barriers, the propagation induces a shift of the spectrum to lower frequencies, so the approximation may be improved by estimating some average propagation frequency shift.

The IMAGINE emission model distinguishes five vehicle types: light vehicles (lv), medium-heavy vehicles (mv), heavy vehicles (hv), mopeds/scooters (mp), and motorcycles (mc). In practice, traffic composition is often specified by the percentages of the first three vehicle types, neglecting the contributions of mopeds and motorcycles.

For the average façade insulation I_{av} a traffic composition of 93/5/2% for lv/mv/hv is assumed. This composition may be considered as a rough average for cities, although large deviations occur between cities. On motorways, in particular on non-urban motorways, the percentage of medium-heavy and heavy vehicles is usually considerably higher than in cities. Consequently, the choice made here of 93/5/2% for lv/mv/hv corresponds to an average urban situation. Driving speeds of 50 km/h are used for the three vehicle types.

In the IMAGINE road emission model, a light vehicle is represented by two point sources at heights 0.01 m and 0.3 m above the road surface, and a medium-heavy or heavy vehicle is represented by two point sources at heights 0.01 m and 0.75 m. The lower point source roughly corresponds to rolling noise (tire-road noise) and the higher noise corresponds to propulsion noise (engine noise). Consequently, a traffic stream composed of light, medium-heavy, and heavy vehicles is represented by point sources at three heights, 0.01 m, 0.3 m, and 0.75 m. For the purpose of the present analysis the sum (logarithmically) of the sound power spectra of the three point sources was calculated. This is illustrated in Figure 5.4, which shows the spectra for the three point sources separately and also the logarithmic sum. The spectra were calculated for the average situation with 930/50/20 vehicles per hour and driving speeds of 50/50/50 km/h for the three vehicle types (lv/mv/hv). From the total spectrum a broadband insulation value I of 28.1 dB was derived.

Figure 5.5 shows single-vehicle sound power spectra for the five vehicle types, for a driving speed of 50 km/h. As a measure of the low-frequency character of the spectrum, the difference between the C-weighted level and the A-weighted level is used. The values of this difference are indicated in the legend of the figure. The difference in low-frequency character between the spectra for lv, mv, hv, and mc is small, while mopeds (mp) are seen to have stronger high-frequency content. Values of the broadband façade insulation I are also indicated in the legend. The differences between the insulation values for the five vehicles types are small, 3 dB at most.

Figure 5.6 shows the spectra for three driving speeds, 30, 50, and 80 km/h. The lowest value of the façade insulation occurs for heavy vehicles at 30 km/h, with I = 26.2 dB. This value is only 2 dB lower than the average value of 28.1 dB derived before.

For comparison, also the Dutch standard road traffic emission model was used to calculate the emission spectrum for the average situation with 930/50/20 vehicles per hour and driving speeds of 50/50/50 km/h for the three vehicle types (lv/mv/hv). The result is shown in Figure 3.7. The insulation value I = 27.1 dB is 1 dB lower than the value I = 28.1 dB obtained before with the IMAGINE emission model. Also, the emission spectrum for porous asphalt (ZOAB) was included instead of dense asphalt (DAB) in Figure 5.7, with an insulation value I = 26.8 dB. However, the effect of road surface on the insulation value appears to be small.

Figure 5.8 shows single-vehicle sound power spectra for the three vehicle types (lv, mv, hv) calculated with the Dutch emission model. Comparison with the IMAGINE spectra shown in Figure 5.5 indicates that there are small differences between the two emission models.

For road vehicles it may be concluded that $I - I_{av}$ is about -2 dB for heavy vehicles at 30 km/h. For practical variations of the traffic composition in a city the magnitude of $I - I_{av}$

is even smaller. Interpolation of these small differences in façade insulation in the QCity model that was shown in Figure 5.1 yields an effect on L_{den} less than 1.3 dB for I - I_{av} = -2 dB. Thus, it may be concluded that the expected façade-insulation correction terms based on the emission spectrum are only small.

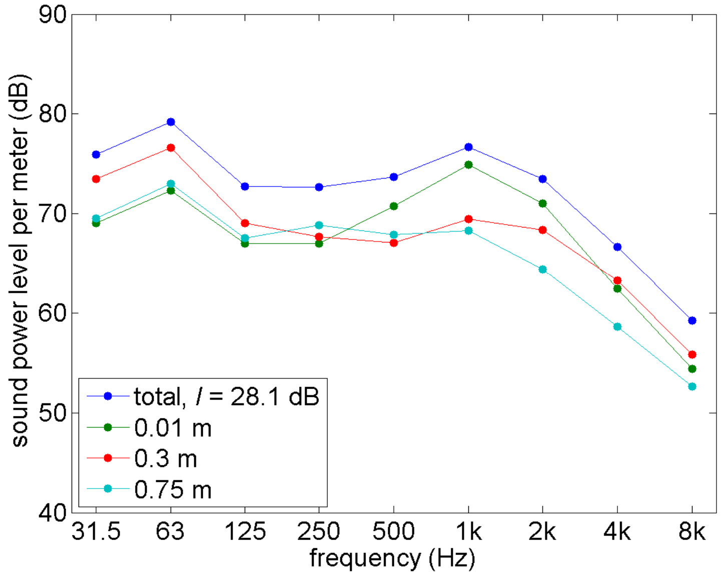

Figure 5.4 Octave-band spectra of the sound power level per meter, calculated with the IMAGINE road emission model, for a situation with 930/50/20 vehicles per hour and driving speeds of 50/50/50 km/h for the three vehicle types (lv/mv/hv). Spectra are shown for the three point sources at 0.01 m, 0.3 m, and 0.75 m, and also the total spectrum (logarithmic sum) is shown. The value of the broadband insulation *I* is indicated in the legend.

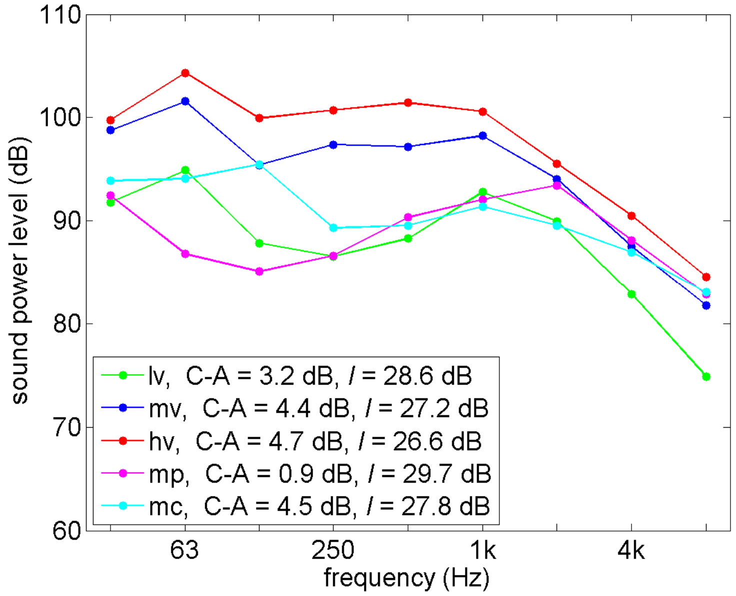

Figure 5.5 Emission spectra calculated with the IMAGINE road emission model, for five different road vehicles, for driving speed 50 km/h. The value of the difference between the C-weighted level and the A-weighted level ('C-A') is indicated in the legend. The value of the broadband insulation *I* is also indicated.

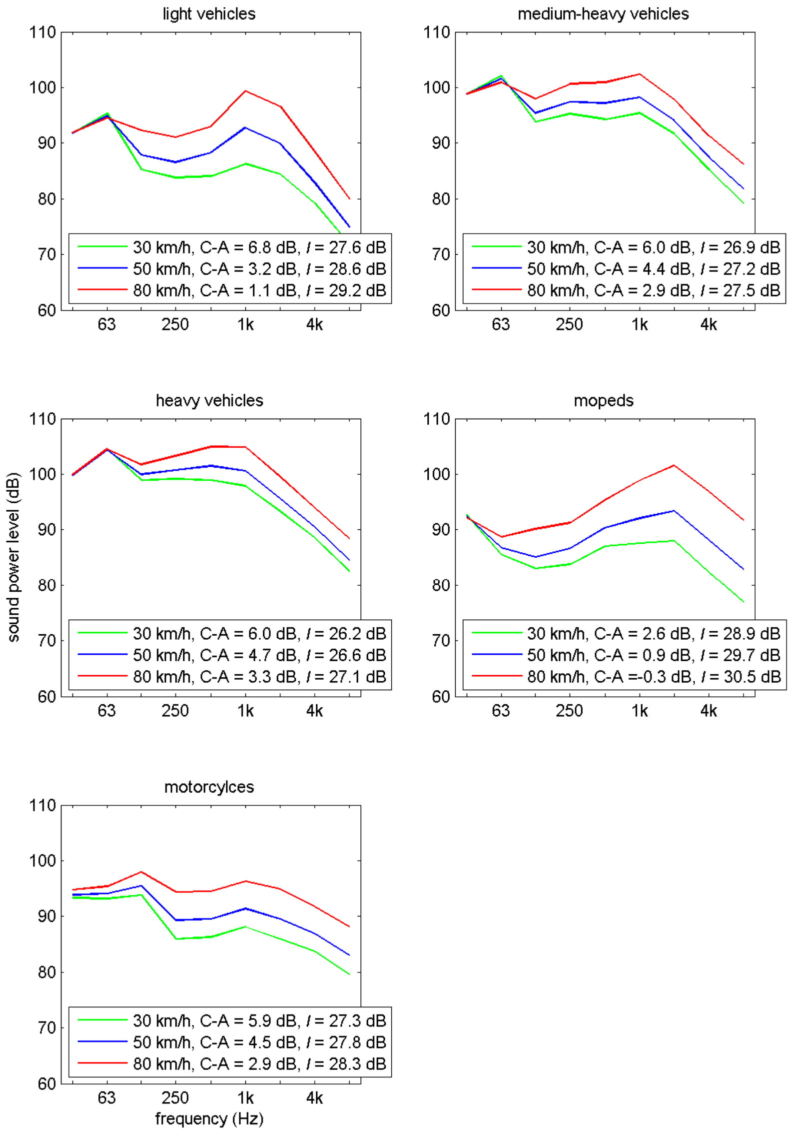

Figure 5.6 Emission spectra calculated with the IMAGINE road emission model, for five different road vehicles and three driving speeds: 30, 50, and 80 km/h. The value of the difference between the C-weighted level and the A-weighted level ('C-A') is indicated in the legend. The value of the broadband insulation *I* is also indicated.

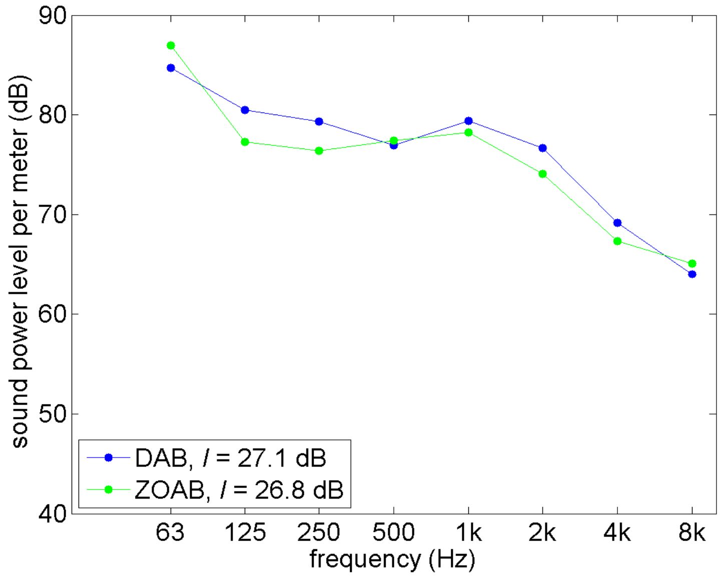

Figure 5.7 Octave-band spectra of the sound power level per meter, calculated with the standard Dutch road emission model, for a situation with 930/50/20 vehicles per hour and driving speeds of 50/50/50 km/h for the three vehicle types (lv/mv/hv). Spectra are shown for dense asphalt concrete (DAB) and porous asphalt (ZOAB). The values of the broadband insulation *I* are indicated in the legend.

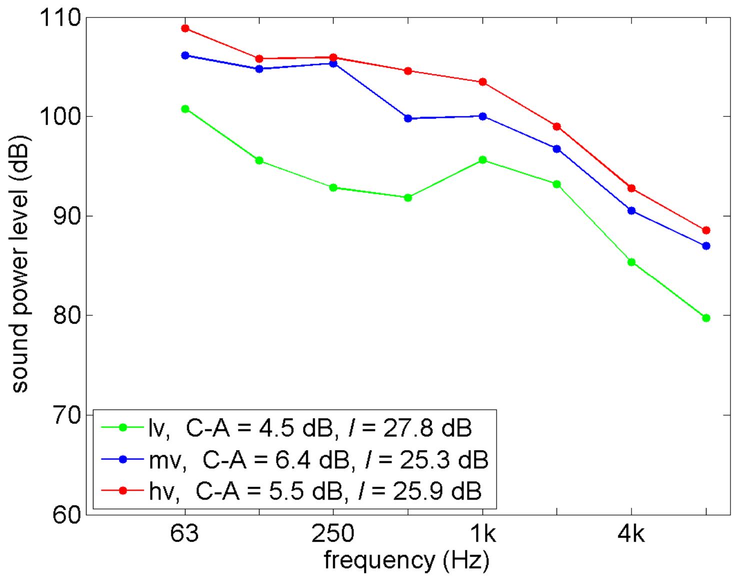

Figure 5.8 Emission spectra calculated with the standard Dutch road emission model, for three different road vehicles, for driving speed 50 km/h and DAB road surface.

5.4.2 Measured noise spectra

The variation of the façade insulation found in the previous section was small, 2 dB at most. In this section it is shown that variations are much larger if measured sound spectra are considered of road and rail traffic noise, ship noise, aircraft noise, and industry noise.

A large set of measured spectra was used from a report for the Dutch Ministry of Environment [Peutz 2003]. For each spectrum a value of the difference between the C-weighted level and the A-weighted level was calculated. This difference is a measure of the low-frequency content of the spectrum, and is indicated here as 'C-A' as in the previous section.

Table 5.3 presents information about the values of 'C-A' found for road traffic, rail traffic, ships, aircraft, and industry noise. Values between 1 and 24 dB have been found. The mean value of C-A is smallest for railway noise and largest for industry noise.

Table 5.3 Information on values of 'C-A' found for road, rail, ship, and aircraft traffic and industry noise [Peutz, 2003].

	Range 'C-A'	Mean value of 'C-A'	Standard deviation
Road traffic	2 – 15 dB	7.1 dB	3.3 dB
Rail traffic	1 – 15 dB	5.3 dB	3.6 dB
Ships	9 – 21 dB	13.8 dB	2.7 dB
Aircraft	2 – 13 dB	9.1 dB	2.0 dB
Industry	6 – 24 dB	13.2 dB	4.4 dB

From the set of spectra spectral shapes of 10 cases were derived: 4 cases of road traffic, 1 of rail traffic, 2 of ship noise, 1 of aircraft noise, and 2 of industry noise. The spectra are shown in Figure 5.9, with values of C-A and I indicated in the legend. The values of I are plotted in Figure 5.10 as a function of C-A. The regression line in this figure corresponds to the equation

$$I = -0.47 \text{ 'C-A'} + 29.2. \qquad (6)$$

This shows that the range of 1-24 dB of C-A values corresponds to a range of 18 – 28 dB of the façade insulation.

Using Eq. (6) and the mean values of C-A in Table 5.3, the values of the mean façade insulation I_{av} may be calculated, which are used in the Q-City formula (3a). The corresponding values of I_{av} are given in Table 5.4. Note that different values of I_{av} are given for different source categories, reflecting the different exposure-response relations for annoyance for different source categories.

Table 5.4 Values of the mean façade insulation I_{av} used in the Q-City formula (3a), derived from the mean values of C-A from Table 5.3.

	Mean value of 'C-A'	Mean façade insulation I_{av} (dB)
Road traffic	7.1 dB	25.9 dB
Rail traffic	5.3 dB	26.7 dB
Ships	13.8 dB	22.7 dB
Aircraft	9.1 dB	24.9 dB
Industry	13.2 dB	23.0 dB

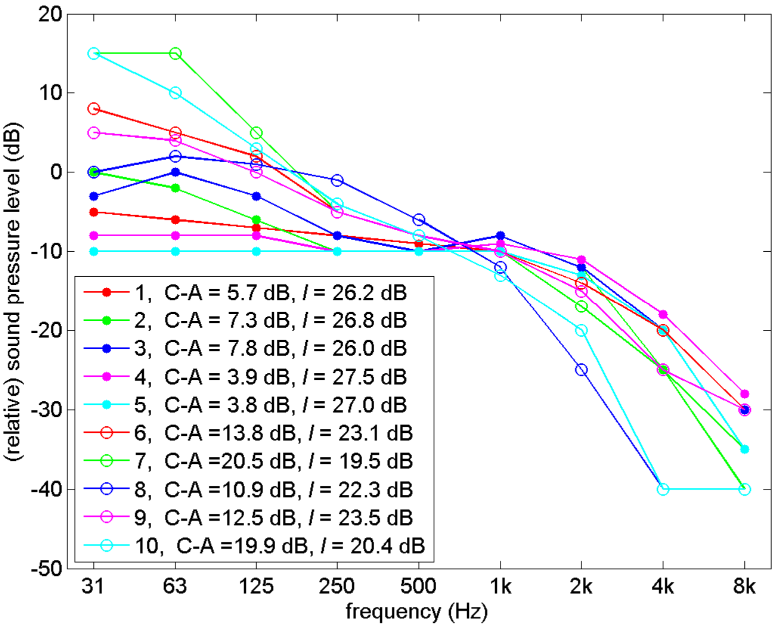

Figure 5.9. Spectra of the relative sound pressure level measured for road traffic (1-4), rail traffic (5), ship noise (6-7), aircraft noise (8), and industry noise (9-10).

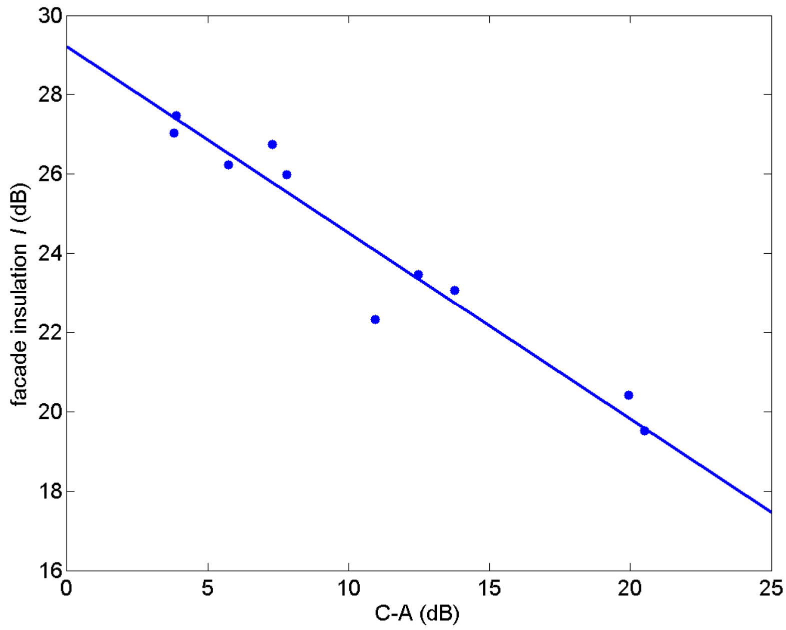

Figure 5.10. Values of insulation I as a function of C-A, from Figure 5.9. The line corresponds to the equation I = -0.47 'C-A' + 29.2.

5.5 CONCLUSION

It is concluded that the preliminary values a_I = -0.0222 and b_I = 1 proposed in QCity can be used for the calculation method presented here. These values are partly supported by results from a recent Norwegian study into the relation between façade insulation and traffic noise annoyance. Although the efficiency (see Section 5.1) derived from the Norwegian study was 100%, which is larger than the efficiency of 67% corresponding to the preliminary QCity values, this may be attributed to the fact that the Norwegian study focused on annoyance 'inside the house', while the model here aims to predict the annoyance 'at home', or 'in and around the house'.

The stepwise procedure for the effect of the noise spectrum is as follows.

1. Determine the A-weighted octave band sound spectrum $L_{A,j}$ for the noise source (or noise situation) that is considered.

2. Calculate the value of the broadband façade insulation with Equation (5).

3. Use value of I_{av} from Table 5.4, or a more appropriate value if this is available in a specific situation or city.

4. Calculate the effect on L_{den} with Eq. (3a).

While again information is missing on the average façade insulation in the original studies on which the exposure-response relation is based, the uncertainty introduced by the value of I_{av} is (largely) eliminated in studies of *changes* or *differences* in façade insulation. The calculation method presented here makes it possible to express effects of improving façade insulation of dwellings, or effects due to variations of the structure of dwellings, facades, and windows, as changes in (expected) annoyance.

6 TEMPORAL VARIATIONS

The prediction of annoyance using exposure-response relationships is usually based on the yearly average of A-weighted equivalent sound levels at the most-exposed façade of the dwelling. This means that the prediction of annoyance not only neglects a possible influence of differences in ambient outdoor levels, indoor levels, and frequency spectrum, but also the influence of differences in temporal distribution (expect for day-evening-night differences). Different types of temporal variations may be distinguished:

- long-term variations (season or meteorological differences)
- short-term variations (peak events, number of events, amplitude modulation)

Evidence for the possible existence of an influence of various types of long-term variations and short-term variations is discussed below. Subsequently, a method to incorporate the influence of some of these characteristics is proposed.

6.1 LONG-TERM VARIATIONS

Given a certain exposure level at the façade, residents' exposure to noise may not be consistent over the duration of the year. Firstly, meteorological conditions may influence the actual exposure at the façade by influencing the propagation of noise. Secondly, it is assumed that season or meteorological conditions may affect residents' exposure to noise by influencing two behaviors: the opening of windows and the use of outdoors space. The increased noise exposure is then presumed to increase annoyance. In moderate climates it is assumed that outdoor activities become more desirable and frequent in residential areas with higher temperature, more sunshine, an absence of precipitation, and an absence of high winds. Window opening is assumed to increase for ventilation purposes as temperature increases. Window opening is presumed to decrease in higher wind and precipitation conditions as residents attempt to shelter their interior living space from the effects of high air velocity and the associated intrusion of moisture or dust through open windows. The resulting relationship between temperature and noise exposure provides a basis for hypothesizing that noise annoyance reactions will be stronger in the summer than the winter season and stronger in warmer than colder climates. Other meteorological variables such as precipitation, sunshine, and wind velocity are not uniformly higher in the winter or summer in all climates and therefore do not predict a simple, universal increase in noise exposure and annoyance in the summer season. Miedema et al (2005) estimated the effect of season and meteorological conditions on the annoyance response to transportation noise in a large database with over 80 000 respondents from 42 studies conducted at different times of year in diverse climates. In a subset of representative probability samples in the Netherlands, who were interviewed as part of a continuous survey, it was found that long-term annoyance by transportation noise is slightly, but statistically significantly higher in summer than in winter. The same seasonal pattern was found in the combined dataset of the other 41 studies, with a difference of about 8 annoyance points (on a 100-point scale) between the peak annoyance in September and the lowest annoyance in March. Also, evidence was found that annoyance is increased by temperature (with a 15°C difference in temperature having about the same effect on annoyance as a 1-3 dB change in noise exposure, although the uncertainties are large), and may be increased by more sunshine, less precipitation, and reduced wind speeds.

6.2 SHORT-TERM VARIATIONS

6.2.1 Peak events and number of events

While the annoyance response is predicted by the equivalent noise level, most of the environmental noise levels found in residential areas consist of individual noise events that may be distinguished in time. A noise event is a noticeable increase in the noise level during a limited time period (several minutes at the most, but usually much shorter), caused for instance by passing aircrafts, trains or vehicles. These individual events may be characterized by the metrics *ASEL* or L_{Amax}, denoting the integrated A-weighted noise levels over the duration of the event and the highest A-weighted noise level during the event, respectively. The question of interest here is whether noise events have stronger adverse effects (annoyance or sleep disturbance) than is reflected in their contribution to the equivalent noise level, and if so, whether these additional adverse effects may be predicted on the basis of *ASEL* or L_{Amax}.

First, it is important to understand what aspects of noise events may cause additional adverse effects. In general, disturbance by noise may occur in several ways:

- Fear or startle responses,
- Attentional responses,
- Disturbance of conversation,
- Sleep disturbance (e.g. awakenings).

In addition, several attitudinal personal factors may influence the response to individual noise events, in particular fear, expectations and perceived avoidability of the noise. The influence of aspects of the individual noise events on specific disturbances is discussed below, as well as the influence of personal factors.

Startle or attentional responses

A sudden increase in the noise level may induce a startle response, particularly when the noise event is unexpected. Even if no startle response is induced, a sudden unexpected event may attract attention and thereby be more disturbing. For most types of transportation noise (air, rail, road), the rise times usually do not justify the application of a penalty, but impulse sound such as those by small firearms are rated as more annoying than road traffic noise at equal levels in the laboratory, with the difference being equivalent to the change in annoyance produced by a 12 dB shift (Vos 2001). Furthermore, results of a field study (Buchta and Vos 1998) showed that at equal noise levels, artillery sounds from large firearms were more annoying than road traffic sounds, with the difference being equivalent to the change in annoyance produced by a 5-dB shift in the yearly average day–night levels of the sounds.

On the basis of the above and additional laboratory studies, a penalty has been proposed by Miedema and Passchier-Vermeer (1999) in the situation of noise events with high rise times. For situations of events with a rise time between 15 and 50 dB/s, a penalty of 5 dB is indicated, while for rise times above 50 dB/s a 10 dB penalty is indicated. When such a penalty is applied, it does not seem necessary to take into account *ASEL* or L_{Amax} as additional predictors. A penalty may be applied on the L_{Aeq} if the proportion of high rise noise events is high and the L_{Aeq} is for a large part determined by these events (for instance at least 10 dB higher L_{Aeq} than without these events). However, to prevent a disproportionate influence of only few events with high rise time, a penalty could rather be applied to each *ASEL* of events with high rise time (>15 dB/s).

Even when rise time of >15 dB/s are not reached, startle responses or attentional responses may occur, particularly in cases where people experience some degree of fear of the source or perceive the source as avoidable or unexpected. Examples of these are the increased annoyance response to low overflying aircrafts, or to powered two wheelers such as mopeds, scooters and motorbikes. It was found that when respondents are frightened or concerned about danger related to the source, the annoyance response is similar to that experienced in respondents without fear at levels of L_{den} up to 19 dB higher (Miedema and Vos 1999). With regard to powered two wheelers a large population survey in the Netherlands (Franssen et al 2004) showed that mopeds (and to a lesser degree motorbikes) were the most annoying source among road traffic noise sources, despite them only being present relatively infrequently in comparison to other road traffic noise sources. In a laboratory study of annoyance by mopeds (Vos 2006), listening tests yielded annoyance ratings for moped noise, while road traffic noise was used as a reference. The *ASEL* was found to be a good predictor of the annoyance rating, with no *additional* predictive value of psycho-acoustic characteristics such as sharpness, roughness or fluctuation strength. Furthermore, it was found that at equal *ASEL* the annoyance rating for mopeds was higher than for road traffic noise, with the difference corresponding to a penalty of about 4.6 dB. This would mean that in the calculation of L_{Aeq}, the *ASEL* of moped events may be given a penalty of 4.6 dB and thereby be weighted more than the *ASEL* of other passing road vehicles. Still, given the high percentages of annoyance by mopeds with respect to other road traffic noise sources observed in surveys, an even higher penalty would be expected. This may be due to the possible underestimation of non-acoustic factors such as fear or perceived avoidability in laboratory settings.

Disturbance of conversation

Loud noise events are expected to be more disrupting for conversation than low noise events, which may not be disruptive at all. Therefore, for the prediction of disturbance of conversation, the *ASEL* or L_{Amax} of events is expected to provide relevant information in addition to L_{Aeq}. However, analysis on survey data around Schiphol Airport (Miedema and Passchier-Vermeer 1999) showed that also low *ASEL* values (<65 dB(A)) importantly contributed to self-reported disturbance of communication, suggesting that rather than disruption also discomfort (having to speak louder, listening more closely) is relevant.

Sleep disturbance

For the prediction of sleep disturbance, the EC (2004) advises on the use of L_{night} (L_{Aeq} between 23-7 h) as the primary indicator for sleep disturbance. However, a key question for policy is whether equivalent sound limit levels offer sufficient protection against sleep disturbance. While analyses on survey data around Schiphol Airport (Miedema et al 2000) showed that the effect of an increase in the number of flights was adequately reflected in the equivalent sound levels as far as annoyance was concerned, this could be different for sleep disturbance. There are indications that some aspects of sleep disturbance are also dependent on the number and temporal distribution of individual noise events over the night (e.g. Basner et al 2010). L_{Amax} and *SEL* of individual events may be more predictive of instantaneous and short term effects such as awakening, (onset of) motility, cardiovascular responses and sleep stage changes (WHO 2009). Therefore, in principle the prediction of effects such as number of awakenings may be improved by additional information on the number (combined with levels) of individual events. Given a certain equivalent level, it can be proven that theoretically the expected response (e.g. the number of awakenings) is highly dependent on the average *ASEL* of events (i.e. with the number of events) and that the maximum level of disturbance should take place at L_{Amax} or *ASEL* levels which are close to the threshold level for awakening or other indicators of sleep disturbance (Miedema and Passchier-Vermeer 1999, EC 2004). However, the assumption was made that the chances of awakening by individual events are independent of each other, which may not be justified. Therefore, before applying penalties or additional indicators, it is important that the contribution of additional indicators such as L_{Amax}, *ASEL* or number of events is verified more thoroughly in field situations.

6.2.2 Amplitude modulation

Another characteristic of noise that may influence the annoyance in addition to the equivalent noise level is the amplitude modulation. The influence of amplitude modulation was investigated in a laboratory study (Vos et al 2010) in which participants were asked to rate several noise excerpts with regard to how annoying they would find the noise if they heard it frequently at home for a longer period of time. In one set of conditions the effect of amplitude modulation (1 Hz) on annoyance was determined for low frequency sinusoidal tones and 1/3-octave noise bands. In a second set of conditions a similar effect was determined for broadband noise. For the low frequency sinusoidal tones, the effect of amplitude modulation (found for the range between 0 and 12 dB) corresponded to a similar increase in annoyance as an increase in the unmodulated sound level of about 5 dB, and for broadband noise this was even 10 dB. For the low-frequency 1/3-octave noise band, the annoyance was not affected by amplitude modulation at all, which might be related to the fact that even in the unmodulated condition this narrow low-frequency noise band is already perceived as being very rough and fluctuating.

The results described above suggest that a penalty between 5 and 10 dB for amplitude modulations should be applied for broadband noise. However, the applied frequency of amplitude modulation in the above cases was 1 Hz, which is higher than the temporal variations that are found in the noise levels of common transportation sources in residential areas, such as those resulting from departing procedures at busy airports, passing trains or passing vehicles on local or regional roads. Therefore, in a third set of conditions in the same study, the annoyance caused by recorded sounds of departing aircraft or passing road traffic was compared to continuous noise with the same spectral content as the sound fragments with the recorded sounds. It was found that ratings were neither significantly affected by source type nor by temporal structure, suggesting that the A-weighted equivalent sound level is a good predictor of annoyance in these situations.

6.3 Conclusion

The following conclusions can be drawn from the overview given above on effects of temporal variations on noise annoyance:

- Small seasonal variations are found in annoyance response at a given noise level, with more annoyance reported in the summer period than in winter.
- For events with a rise time between 15 and 50 dB/s, a penalty of 5 dB is indicated, while for rise times above 50 dB/s a 10 dB penalty is indicated.
- Based on laboratory studies, the *ASEL* of moped events and other powered two wheelers may be given a penalty of 4.6 dB. However, this may still give an underestimation because of the larger influence of non-acoustic factors such as fear or perceived avoidability outside the laboratory.
- For conversation and sleep disturbance it may be derived theoretically that the highest adverse response at a given L_{Aeq} should be expected just above the threshold level (L_{Amax} or *ASEL*) for an effect. However, it is important that the contribution of additional indicators such as L_{Amax}, *ASEL* or number of events is verified more thoroughly in field situations.
- The maximum adjustment needed to account for the presence of amplitude modulation for broadband noise ranges between 5 and 10 dB. However, this does not apply to the type of temporal variations that are found in the noise levels of common transportation sources in residential areas. In these situations, the A-weighted equivalent sound level is a good predictor of annoyance.

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