**Proceedings of the Institute of Acoustics & Belgium Acoustical Society**
**Noise in the Built Environment, Ghent, 29-30 April 2010**

# MODEL STUDY OF URBAN TRAFFIC NOISE AND QUIET FACADES, IN RELATION WITH ANNOYANCE AND SLEEP DISTURBANCE

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## ABSTRACT
Annoyance and sleep disturbance caused by urban traffic noise are usually predicted from sound levels at the most exposed facades of dwellings. The predictions may be refined by taking into account sound levels at the other facades, in particular quiet facades. In this article a study is presented of the benefits of quiet facades in a large urban area in the Netherlands. Sound levels at all facades of dwellings were calculated with an engineering approach, taking into account traffic intensities on the roads. The sound levels were used for a logistic regression of self-reported annoyance and sleep problems, in a large population-based cohort study including over 18000 subjects.

## 1 INTRODUCTION

Traffic noise in cities causes annoyance and sleep disturbance of the inhabitants. Prevalence of these harmful effects in an urban population can be predicted with exposure-response relations, which are commonly based on exposure levels at the most exposed facades of dwellings.[1] For annoyance the exposure is represented by the day-evening-night level $L_{den}$ at the most exposed façade. For sleep disturbance the night level $L_{night}$ at the most exposed façade is employed.
The 'true' exposure of people to traffic noise depends on the sound levels as a function of time and position in the city. The level at the most exposed façade of a dwelling is a crude approximation for the exposure, and its use is justified mainly because statistically significant relations are found between the level at the most exposed façade and self-reported annoyance and sleep disturbance.[2]
A more accurate representation of the exposure may be obtained by using not only the level at the most exposed façade, but also the following acoustical quantities[3,4]
- acoustic insulation of a dwelling,
- sound level at the *least* exposed façade of a dwelling (quiet façade),
- mean sound level in the direct vicinity of a dwelling, say within a radius of 200 m.

In this study we focus on the second quantity, the sound level at the quiet façade of a dwelling.
A quiet façade may provide the inhabitants the possibility to 'escape' from the noise, either by the presence of a quiet garden or balcony at the back of the house, or by the possibility to choose a bedroom at the quiet side of the house. Consequently, inhabitants of a house *with* a quiet façade may be less annoyed or sleep disturbed (on the average) than inhabitants with equal sound level at the most exposed façade but *without* a quiet façade (see Fig. 1).

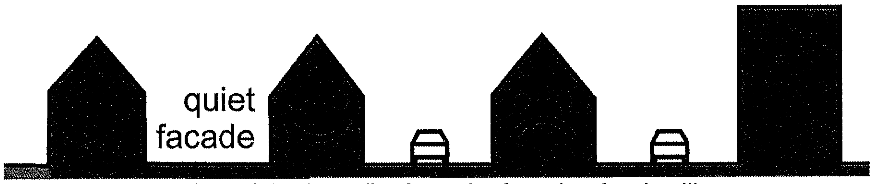

Figure 1. Illustration of the benefit of a quiet façade of a dwelling.

In this paper we present preliminary results of a study of the relation between road traffic noise and self-reported annoyance and sleep disturbance in a large group of 18000 respondents living in an urban area around the city of Eindhoven (cohort study). The study focuses on the possible positive effects of quiet facades of the dwellings.
In a previous study, de Kluizenaar *et al.*[5] have presented evidence for a relation between sleep disturbance and the traffic noise level at the most exposed façade of a dwelling. In the present study we have included traffic noise levels at the most and the least exposed façade of a dwelling.

We have performed noise calculations for the urban area with two different noise models, the Dutch standard model for road traffic noise (SRM) and a street-canyons model (SCM) that was recently developed by Salomons *et al.*[4] The SCM model is expected to give more realistic results at shielded areas in a city, for example at quiet facades. To obtain an impression of the effects of noise model uncertainties, we have included both models in the present study.

# 2 NOISE EXPOSURE

## 2.1 Calculations

Figure 2 shows the urban area of interest in this study. The large city slightly above the center is Eindhoven. Figure 3 shows an example of calculated sound levels ($L_{den}$) at facades of dwellings in a small region in Eindhoven. The figure shows that sound levels at facades shielded from traffic noise are lower than sound levels at facades directly exposed to traffic noise.

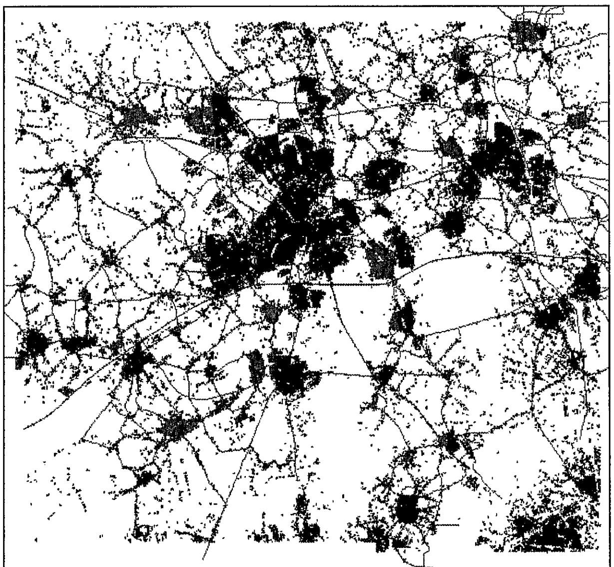

Figure 2. Urban area of approximately 40 x 40 km$^2$, with buildings (gray), roads (green), and noise barriers (red).

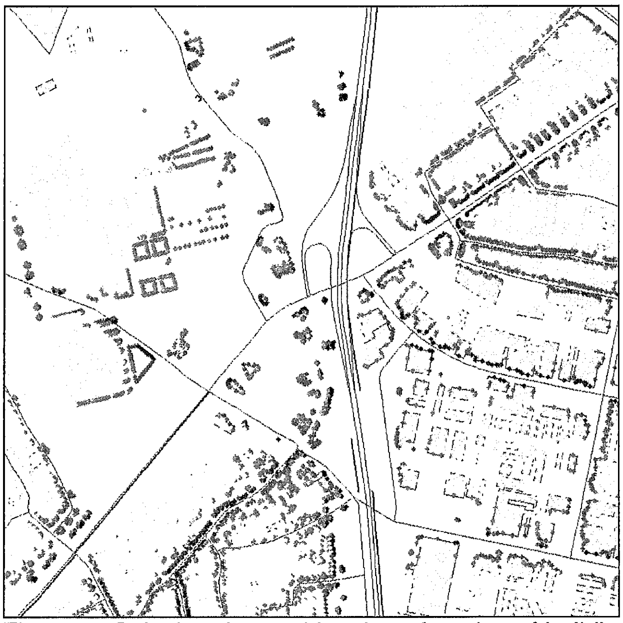

Figure 3. Calculated sound levels at facades of buildings, in a small region at the boundary of Eindhoven. The color of the dots represent the $L_{den}$ sound level: light green 50-55 dB, yellow 55-60 dB, orange 60-65 dB, red 65-70 dB, and purple 70-75 dB. The north-south road in the middle (green lines) has noise barriers at both sides (red lines).

## 2.2 Exposure at most exposed facade

Figure 4 shows the exposure distributions calculated with the SRM and SCM models. Results for Amsterdam[4] have been included for comparison. Differences between the two models occur in particular at low sound levels, corresponding to shielded areas.

The SCM exposure distribution for Amsterdam shows two distinct maxima, one around 68 dB and one around 50 dB. The maximum around 68 dB represents mainly directly exposed dwellings and the maximum around 50 dB represents mainly shielded dwellings. The SCM exposure distribution for the Eindhoven region has a considerably different shape, with a single maximum around 50 dB and a continuous decrease to zero at higher levels. The SRM distributions have a similar shape as the SCM distributions, but the (lower) maximum occurs around 45 dB instead of 50 dB.

The difference between the exposure distributions of Amsterdam and the Eindhoven region originates primarily from the difference in the distribution of traffic intensity on the road network. This will be demonstrated quantitatively in a future publication. Here we present a qualitative discussion. The sound level at a directly exposed dwelling is to a large extent determined by the traffic intensity on the road near the dwelling. The sound level at a shielded dwelling is determined by roads in a larger region, and furthermore depends on the heights of the shielding buildings. Figure 5 shows the vehicle intensity distributions for motorways and other roads in the Eindhoven region. Here we define a motorway as a road with a driving speed of 80 km/h and higher. Figure 6 shows the corresponding distributions for Amsterdam. The vehicle intensities in the Eindhoven region are considerable lower than in Amsterdam. The mean intensity is a factor 3.5 lower for motorways and a factor 2.2 lower for other roads. These factors correspond to a lowering of sound levels by 3.5 to 5.5 dB. Building heights in the Eindhoven region are also considerably lower than in Amsterdam. In the Eindhoven region the large majority of the buildings is about 9 m high, while in Amsterdam there are also many buildings with heights up to 20 m. Consequently, screening attenuation by buildings in the Eindhoven region is smaller (on the average) than in Amsterdam. This explains why the two maxima observed in the Amsterdam exposure distribution merge into a single maximum in the Eindhoven region.

There are various other differences between the traffic data for Amsterdam and the Eindhoven region, such as the distribution of vehicle types (light, medium-heavy, and heavy vehicles) and the distribution of vehicles over the three relevant time periods (day, evening, and night). Typically 90% or more of the vehicles are light vehicles, and about 60% of the traffic is in the day, 30% in the evening, and 10% in the night. There are also differences in the road surface types. Most of the roads have a dense asphalt concrete surface, but a considerable number of roads have different surfaces such as porous asphalt or cobble stones.

## 2.3 Exposure at quiet facades

Figure 7 shows the distributions of the level difference ($Q$) between $L_{den}$ at the most exposed façade and $L_{den}$ at the least exposed façade of a dwelling. The difference Q varies between zero and about 25 dB. A similar distribution was found for Amsterdam.[4]

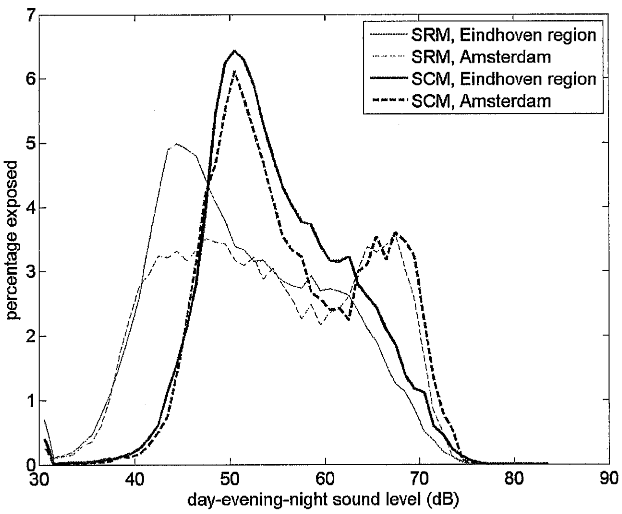


Figure 4. Exposure distributions calculated with the SRM and SCM models. Shown is the percentage of dwellings exposed as a function of the day-evening-night level ($L_{den}$) at the most exposed façade.

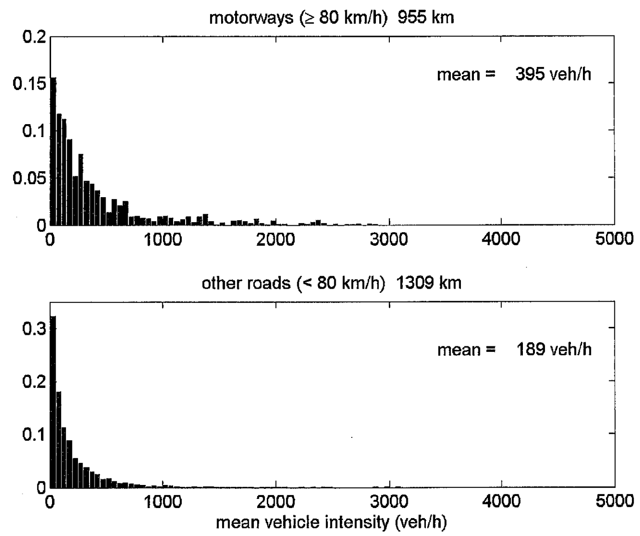


Figure 5. Distributions of traffic intensity for the Eindhoven region.

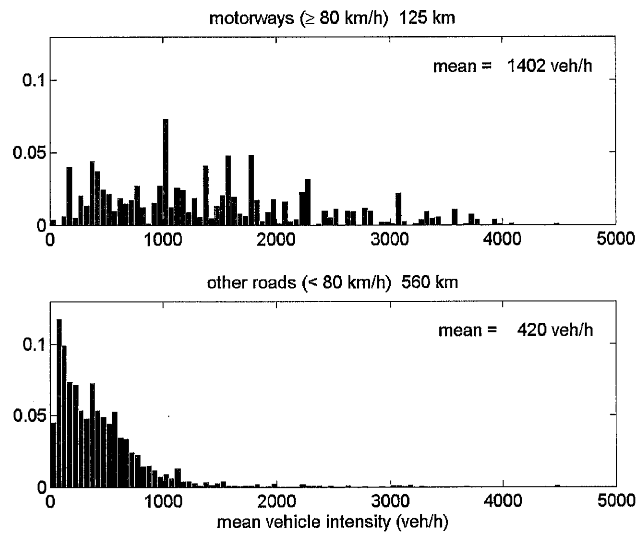


Figure 6. Distributions of traffic intensity for Amsterdam.

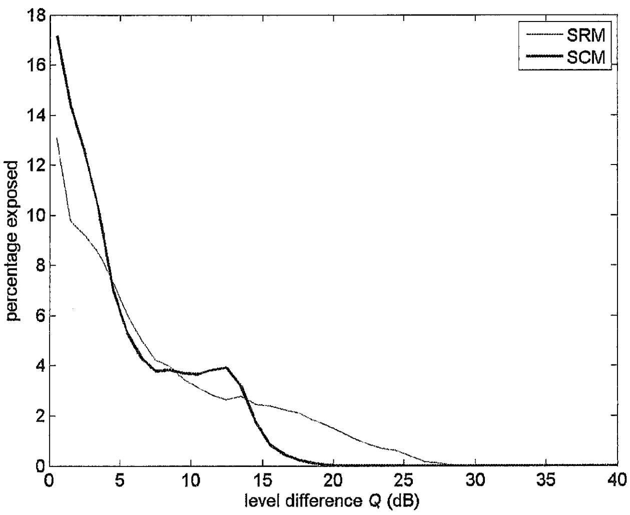


Figure 7. Distribution of the level difference ($Q$) between $L_{den}$ at the most exposed façade and $L_{den}$ at the least exposed façade of a dwelling, calculated with the SRM and SCM models.

# 3 ANNOYANCE AND SLEEP DISTURBANCE

In the cohort study, annoyance by traffic noise and sleep disturbance (morning tiredness) were reported by 18000 inhabitants of the urban area, as dichotomous variables ('yes or no'). The relation between traffic noise exposure and annoyance and sleep disturbance was investigated by means of logistic regression.

Traffic noise exposure of a dwelling was represented by two quantities:
- $L_{den,max}$ the day-evening-night level at the most exposed façade,
- $Q = L_{den,max} - L_{den,min}$ the difference in $L_{den}$ between the most and the least exposed façade.
It should be noted that $L_{den,max}$ is usually indicated simply as $L_{den}$ (also in the previous sections).

Annoyance ($a$) and sleep disturbance ($s$) were expressed as logistic functions:

$$a = \frac{1}{1+\exp(-z)}$$

$$s = \frac{1}{1+\exp(-z)}$$

where $z$ is a measure of the noise exposure. We considered four different models for quantity $z$:

model 1: $z = \alpha + \beta_1 L_{den,max}$

model 2: $z = \alpha + \beta_1 L_{den,max} + \beta_2 Q$

model 3: $z = \alpha + \beta_1 L_{den,max} + \beta_2 Q + \beta_3 L_{den,max} Q$

model 4: $z = \alpha + \beta_1 L_{den,max} + \beta_2 Q + \beta_3 L_{den,max} Q + \text{(terms for confounders)}$

Here $\alpha$ and $\beta_i$ ($i$ = 1, 2, 3) are adjustable parameters that are optimized by logistic regression to the cohort data. The confounders for model 4 include age, sex, education, and work situation for annoyance, and several others for sleep disturbance.[5]

Preliminary results indicate that all parameters $\beta_i$ ($i$ = 1, 2, 3) are statistically significant, so the product term $\beta_3 L_{\text{den,max}} Q$ is a significant extension of model 2. The interpretation of the product term is that the benefit of a quiet facade depends on the exposure at the most exposed facade. This agrees with the approach presented before in the Q-City project.[3]

In the Q-City project, a quantity $L_{\text{den,q}}$ was defined as follows:

$$L_{\text{den,q}} = L_{\text{den,max}} + \left[a(Q - Q_{\text{av}})L_{\text{den,max}} + b(Q - Q_{\text{av}})\right]$$

with $a$ = -0.016 and $b$ = 0.7. The quantity in square brackets is a correction for the effect of a quiet facade. Quantity $Q_{\text{av}}$ is an average value of $Q$. Here we use the value $Q_{\text{av}}$ = 10 dB. Figure 8 shows that the quiet facade correction is negative for $Q > Q_{\text{av}}$ and positive for $Q < Q_{\text{av}}$. The correction is larger for higher levels $L_{\text{den,max}}$ at the most exposed facade. The Q-City approach was a first indicative approach for calculating the effect of a quiet facade, and was *not* based on extensive noise surveys including the effect of quiet facades. Therefore we are currently working on a calculation scheme based on extensive noise surveys, such as the survey for the Eindhoven region considered in this paper.

Finally it is interesting to derive an expression for the quantity $L_{\text{den,q}}$ with the logistic model. Using the relation $L_{\text{den,max}} = L_{\text{den,q}}(Q = Q_{\text{av}})$ with the logistic model 3, we find the equation

$$\alpha + \beta_1 L_{\text{den,max}} + \beta_2 Q + \beta_3 L_{\text{den,max}} Q = \alpha + \beta_1 L_{\text{den,q}} + \beta_2 Q_{av} + \beta_3 L_{\text{den,q}} Q_{av}$$

Solving for $L_{\text{den,q}}$ yields

$$L_{\text{den,q}} = \frac{\beta_1 L_{\text{den,max}} + \beta_2 Q - \beta_2 Q_{av} + \beta_3 L_{\text{den,max}} Q}{\beta_1 + \beta_3 Q_{av}}$$

Preliminary results indicate that also with this approach the quiet facade correction $L_{\text{den,q}} - L_{\text{den,max}}$ is negative for $Q > Q_{\text{av}}$ and positive for $Q < Q_{\text{av}}$, but that the variation of the correction with $L_{\text{den,max}}$ is different from the Q-City prediction.

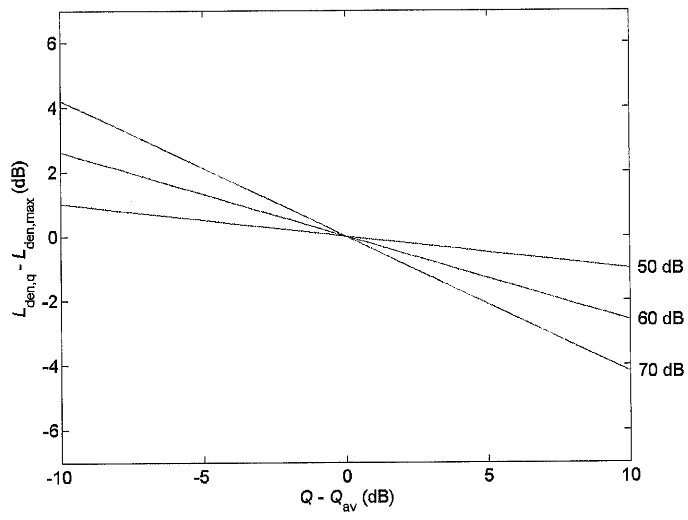


Figure 8. Quiet-side correction as a function of $Q$-$Q_{\text{av}}$, for different values of $L_{\text{den,max}}$ (50, 60, and 70 dB), calculated with the preliminary Q-City calculation scheme.

# 4 CONCLUSIONS

Preliminary results were presented of a study of road traffic noise exposure in a 40 x 40 km area near the city of Eindhoven in the Netherlands. Sound levels at all facades of dwellings were calculated with an engineering approach, taking into account traffic intensities on the roads. The exposure distribution of the sound level at the most exposed façades of dwellings was presented and compared with the distribution for the city of Amsterdam. Differences were discussed and qualitatively explained by differences in the distributions of vehicle intensities and building height.

Sound levels at the *least* exposed facades were also considered. The difference, *Q*, between the level at the most exposed façade and the least exposed façade varies between zero and about 25 dB. The difference *Q* is a parameter of the Q-City model[3,4] for predicting traffic noise exposure and sleep disturbance including the benefit from a quiet façade. The numerical parameters of the Q-City model still have to be determined from noise surveys.

As a first step in this direction, we have performed statistical analysis of self-reported annoyance and sleep problems in the Eindhoven region, in a large population-based cohort study including over 18000 subjects. We have included the sound levels at the most exposed facades and also the level difference *Q* in the analysis. Preliminary results indicate that expected annoyance decreases with increasing *Q* (at fixed sound level at the most exposed façade), indicating that there is a positive effect from a quiet façade. Further work is needed to confirm this and possibly to derive a quantitative prediction scheme similar to the Q-City model.

# 5 REFERENCES

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