Annoyance from Transportation Noise: Relationships with Exposure Metrics DNL and DENL and Their Confidence Intervals

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We present a model of the distribution of noise annoyance with the mean varying as a function of the noise exposure. Day–night level (DNL) and day–evening–night level (DENL) were used as noise descriptors. Because the entire annoyance distribution has been modeled, any annoyance measure that summarizes this distribution can be calculated from the model. We fitted the model to data from noise annoyance studies for aircraft, road traffic, and railways separately. Polynomial approximations of relationships implied by the model for the combinations of the following exposure and annoyance measures are presented: DNL or DENL, and percentage "highly annoyed" (cutoff at 72 on a scale of 0–100), percentage "annoyed" (cutoff at 50 on a scale of 0–100), or percentage (at least) "a little annoyed" (cutoff at 28 on a scale of 0–100). These approximations are very good, and they are easier to use for practical calculations than the model itself, because the model involves a normal distribution. Our results are based on the same data set that was used earlier to establish relationships between DNL and percentage highly annoyed. In this paper we provide better estimates of the confidence intervals due to the improved model of the relationship between annoyance and noise exposure. Moreover, relationships using descriptors other than DNL and percentage highly annoyed, which are presented here, have not been established earlier on the basis of a large dataset. *Key words*: day–evening–night level, day–night level, DENL, DNL, noise annoyance, noise pollution, transportation noise. *Environ Health Perspect* 109:409–416 (2001). [Online 29 March 2001]
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Lambert et al. (*1*) estimated that in the European Union (EU) approximately 77 million people (i.e., 22% of the total population of the EU in 1994) are exposed to a transportation noise level (L_{Aeq}) exceeding 65 dB during the day, which many countries consider to be unacceptable. In 1994, almost 170 million Europeans (49%) lived in "gray zones," areas that do not ensure acoustic comfort to residents (*1*). Depending on the country, road traffic noise annoyed between 20% and 25% of the population (*1*). Even though the uncertainty of these estimates is very large, there is no doubt about the high prevalence of noise annoyance in the EU.

A recent survey in Muscat City, Oman, illustrates that noise and noise annoyance are not confined to the industrialized societies, but are quickly increasing in cities in the developing countries (*2*). The length of the paved roads in Muscat City increased from ≤ 50 km in 1975 to 156 km in the old part of the city and 1,213 km in the entire city in 1995. This explains the finding that in 1995 lack of quietness caused the highest dissatisfaction in a sample of 452 inhabitants. It was higher than the dissatisfaction with the 12 other aspects of the environment that were rated, such as public facilities and safety.

These figures illustrate that noise annoyance is widespread in the industrialized countries, as well as in urban areas in the developing countries. The growing transportation network with increasing traffic densities is a primary cause of the high prevalence of noise annoyance.

For making policy to control environmental noise, it is important to have a set of relationships that show how annoyance levels are associated with given noise exposure levels. Many studies have been conducted to establish such relationships. However, doubt regarding the predictability of noise annoyance has impeded the acceptance of the exposure–response relationships that have been proposed.

One cause of this doubt is that the studies show a large variation in individual annoyance reactions to the same noise exposure level. The other cause of doubt regarding the predictability of noise annoyance is that attempts to integrate the results from different studies (*3–5*) show that there is a large variation in the relationships found in different studies. The large individual variation and the large study variation suggest that it is impossible to predict annoyance with sufficient accuracy.

Indeed, the annoyance response of a particular individual or a group of individuals can be predicted on the basis of the exposure only with a large amount of uncertainty. This uncertainty can be described by the prediction interval for individuals or groups around the exposure–response curves. However, in most cases the uncertainty regarding individual or group reactions is not what matters for noise policy. Most policy is made with a view to the overall reaction to exposures in a population. This means that it is not the uncertainty with respect to the prediction of an individual or group reaction that is important, but it is the uncertainty regarding the exact relationship between exposure and response in the population. The accuracy of the estimation of this relationship is described by the confidence interval around the curve. If properly established, the confidence interval takes into account the variation between individuals as well as the variation between studies.

The distinction between the types of uncertainty (regarding an individual or group reaction or regarding the location of the curve) and their relevance to policy making is as important as it is subtle. In this paper we present a type of exposure–response curve that was established earlier (*3–5*) as well as curves with other descriptors of the exposure and the annoyance, together with the confidence intervals of these curves.

Miedema and Vos (*5*) presented synthesis curves for aircraft, road traffic, and railway noise. An attempt was made to find the 95% confidence intervals around the exposure–response curves, taking into account the variation between individuals and studies. These curves were based on all studies examined by Schultz (*3*) and Fidell et al. (*4*) for which day–night level (DNL) of noise and percentage of "highly annoyed" persons (%HA) meeting certain minimal requirements could be derived, augmented by a number of additional studies. Consequently, that synthesis was more comprehensive than the previous ones. Moreover, the kind of errors and inaccuracies found in the previous syntheses were avoided (*6*).

Here we improve upon the method used to establish the confidence intervals. We analyzed the same data, but the model of the relationship between exposure and annoyance is more sophisticated and better suited for the data. Using the more appropriate model gives the relationships and their confidence intervals a firmer basis. The resulting relationships and their 95% confidence intervals do not differ much from the ones published previously (*5*). The confidence intervals indicate that, even though there is considerable variation between individuals and between studies, the uncertainty regarding the location of the

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relationships between noise exposure and annoyance is rather limited.

In the approach taken in this paper, the entire distribution of annoyance reactions is modeled as a function of the noise exposure. Consequently, any annoyance measure that summarizes this distribution (i.e., %HA or another measure) can be calculated as a function of the exposure level. In addition to the relationships between DNL and annoyance, relationships that use another noise metric, day–evening–night level (DENL) of noise, are presented. DENL has been proposed as the noise exposure metric for the European Union (*7*). This is the first analysis of relationships using descriptors other than DNL and %HA, based on a large data set.

Noise Metrics and Annoyance Measures

Previous synthesis studies used DNL as the descriptor of noise exposure. This noise descriptor is defined in terms of the L_{Aeq} (average levels) during daytime and nighttime, and applies a 10-dB penalty to noise in the night:

$$\mathrm{DNL} = 10 \log \left[(15/24) \times 10^{LD/10} + (9/24) \times 10^{(LN+10)/10}\right]$$

Here LD and LN are the long-term L_{Aeq} as defined by the International Standards Organization (*8*) for the day 0700–2200 hr and the night 2200–0700 hr, respectively. DNL is used in the United States.

A noise metric related to DNL is DENL. It is defined in terms of the average levels during daytime, evening, and nighttime, and applies a 5-dB penalty to noise in the evening and a 10-dB penalty to noise in the night:

$$\mathrm{DENL} = 10 \log \left[(12/24) \times 10^{LD/10} + (4/24) \times 10^{(LE+5)/10} + (8/24) \times 10^{(LN+10)/10}\right]$$

Here LD, LE, and LN are the A-weighted long-term L_{Aeq} (*8*) for the day (0700–1900 hr), evening (1900–2300 hr), and night (2300–0700 hr) determined over the year at the most exposed facade. DENL has been proposed as the new uniform noise metric for the European Union (*7*).

The use of DNL or DENL is supported by a recent study that investigated which noise metrics best predict annoyance from aircraft noise (*9*). The authors concluded that the outcome of their analyses of available data sets supports the use of metrics based on L_{Aeq} and the application of a 10-dB penalty to nighttime noise. The available data were not a suitable basis for a conclusion regarding a penalty for noise in the evening. Results are presented here for both DNL (used in previous synthesis studies and being used in the United States) and DENL (new metric for the European Union) because both measures are relevant.

Annoyance questions in different studies do not use the same number of response categories. Some questions have only 3 response categories, whereas others use as many as 11 categories. The translation of such scales into comparable annoyance measures for different studies is not trivial. Here all sets of response categories were translated into a scale from 0 to 100. The translation is based on the assumption that a set of annoyance categories divides the range from 0 to 100 in equally spaced intervals. The general rule used to determine the position of a category boundary on a scale from 0 to 100 is $\mathrm{score}_{\mathrm{boundary}\ i} = 100i/m$ (Table 1). Here i is the rank number of the category boundary, starting with 0 for the lower boundary of the lowest annoyance category, and m is the number of categories.

The distribution of the annoyance scores at a given noise exposure level can be summarized in various ways. Often a cutoff point is chosen on the scale, and the percentage of the responses exceeding the cutoff is reported (*3–5*). If the cutoff is 72 on a 0–100 scale, then the result is called the percentage of highly annoyed persons (%HA); with a cutoff at 50 it is the percentage "annoyed" (%A), and with a cutoff at 28 it is the percentage "(at least) a little annoyed" (%LA). An alternative to these types of measures is the average annoyance score.

Data

In the last 7 years, TNO in Leiden, The Netherlands, has compiled an archive of original data sets from studies on annoyance caused by environmental noise. These studies concerned different modes of transportation (aircraft, road traffic, and railway) and were carried out in Europe, North America, and Australia. As far as possible, a common set of variables is derived for all studies which includes, among others, noise exposure measures and annoyance measures. Table 2 gives an overview of the studies for which it was possible to derive DNL and %HA in such a way that they satisfy established criteria (*5*). Extreme exposure levels (DNL < 45 or > 75 dB) were excluded from the analyses because there is no practical need for information concerning the annoyance at these extreme levels, and the risk of unreliable data is high at these extremes. (The risk of unreliable noise data is high at very low levels, whereas the risk of selection of "survivors" is high at very high levels). The derivation of DNL and %HA has been discussed elsewhere (*5*). Here that report is supplemented with a discussion of the derivation of the additional measures that are used in this paper.

We also use DENL as a descriptor of the noise exposure, as a possible alternative for DNL. For most studies in Table 2 the L_{Aeq}s that are needed for calculating DENL could be derived in the same way as the L_{Aeq}s that are needed for calculating DNL (*5*). However, DNL was given or estimated directly for various studies, indicated in Table 2, and no information regarding the time pattern of the L_{Aeq} was available for these studies. For these studies DENL is estimated from DNL on the basis of the general rules that are derived in the Appendix. An exception to these rules was made for three airports in the Australian Five Airport Survey (AUL-210) because some information was available, in particular regarding the existence of a nighttime curfew. For Sydney and Adelaide, such a curfew existed so that the hourly L_{Aeq} was expected to drop sharply after 2200 hr. Consequently, the difference, DENL – DNL, was expected to be larger than for most other airports (~ 0.6 dB) but still smaller than the value obtained when the level drops to zero between 2200 and 2300 hr (1.56 dB; Appendix). Thus, a better rule for these airports is DENL = DNL + 1.2. For Melbourne the time pattern resembled that of road traffic more than the usual time pattern of aircraft noise, so that the difference, DENL – DNL, was expected to be smaller than for most other airports (~ 0.6 dB), but still larger than for road traffic (~ 0.2 dB; Appendix). Thus, a better rule in this case is DENL = DNL + 0.3.

Here we model the distribution of annoyance responses as a function of the noise exposure. The input needed for estimating the parameters of the annoyance distribution is either the individual annoyance responses combined with the individual exposure levels, or the distribution of the annoyance responses per noise exposure class. This information was available (*5*) for most studies in Table 2. For some studies, the distribution of the response over the original annoyance categories was not known, but only %HA (and the percentage not highly annoyed). Because the more detailed distribution was not available for these studies, the distributions of responses over the two categories (not highly annoyed, highly annoyed) were used as input.

Table 1. Boundary quantifications for different annoyance scales.

No. of effective categories	Boundary quantifications
3	0-33-67-100
4	0-25-50-75-100
5	0-20-40-60-80-100
6	0-17-33-50-67-83-100
7	0-14-28-43-57-72-86-100
10	0-10-20-_-80-90-100
11	0-9-18-_-82-91-100

We applied a specific procedure to the distribution of annoyance responses if the annoyance question was preceded by a “filter” question (e.g., Do you hear the noise from road traffic? never, sometimes, often, always) on the basis of which the annoyance question was skipped for some respondents (e.g., those who answered “never”). The respondents who skipped the annoyance question can be assumed to have low annoyance. The present analyses are more sensitive to the form of the entire distribution than the previous procedure (*5*), where only the relationship of %HA with the noise exposure was modeled. For establishing that relationship, it was sufficient to assume that respondents who skipped the annoyance question were not highly annoyed (this could technically be done by assigning them to the lowest annoyance category). Here, because of the uncertainty regarding their exact annoyance level, the two lowest annoyance categories were combined if a filter was used, and the respondents who skipped the annoyance question were assigned to this category. This minimized the risk that annoyance was underestimated due to the use of a filter question.

Table 2. Data sets used to establish the relationships between noise exposure and annoyance.

Fields’ code (*6*)	Name of survey (year)	Determination of DENL
Aircraft		
AUL-210	Australian Five Airport Survey (1980)	
	Richmond & Perth	*
	Sydney & Adelaide	DNL + 1.2
	Melbourne	DNL + 0.3
CAN-168	Canadian National Community Noise Survey (1979)	*
FRA-016	French Four-Airport Noise Study (1965)	*
FRA-239	French Combined Aircraft/Road Traffic Survey (1984)	
NET-240	Schiphol Combined Aircraft/Road Traffic Survey (1984)	
NOR-311	Oslo Airport Survey (1989)	*
NOR-328	Bodo Military Aircraft Exercise Study (1991–1992)	*
NOR-366	Vaernes Military Aircraft Exercise Study (1990–1991)	*
SWE-035	Scandinavian Nine-Airport Noise Study (1969, 1970,1971, 1972,1974, 1976)	*
SWI-053	Swiss Three-City Noise Survey (1971)	*
UKD-024	Heathrow Aircraft Noise Survey (1967)	
UKD-242	Heathrow Combined Aircraft/Road Traffic Survey (1982)	
UKD-238	Glasgow Combined Aircraft/Road Traffic Survey (1984)	
USA-022	U.S. Four-Airport Survey (phase I of Tracor Survey) (1967)	
USA-032	U.S. Three-Airport Survey (phase II of Tracor Survey) (1969)	
USA-044	U.S. Small City Airports (Small City Tracor Survey) (1970)	
USA-082	LAX Airport Noise Study (1973)	*
USA-203	Burbank Aircraft Noise Change Study (1979)	*
USA-204	John Wayne Airport Operation Study (1981)	*
USA-338	U.S.A. 7-Air Force Base Study (1981)	*
Road traffic		
BEL-122	Antwerp Traffic Noise Survey (1975)	*
BEL-137	Brussels Traffic Noise Survey (1976)	*
CAN-120	Western Ontario University Traffic Noise Survey (1975)	
CAN-121	Southern Ontario Community Survey (1975/1976)	*
CAN-168	Canadian National Community Noise Survey (1979)	
FRA-092	French Ten-City Traffic	
NET-276	Netherlands Tram and Road Traffic Noise Survey (1993)	
NET-361	Netherlands Environmental Pollution Annoyance Survey (1983)	*
NET-362	Arnhem Road Traffic Study (1984)	*
SWE-142	Stockholm, Visby, Gothenburg Traffic Noise Study (1976)	*
SWE-165	Gothenburg Tramway Noise Survey (1976)	
SWI-053	Swiss Three-City Noise Survey (1971)	
SWI-173	Zurich Time-of-Day Survey (1978)	
UKD-071	B.R.S. London Traffic Noise Survey (1972)	
UKD-072	English Road Traffic Survey (1972)	
UKD-157	London Area Panel Survey (1977/1978)	
UKD-242	Heathrow Combined Aircraft/Road Traffic Survey (1982)	
UKD-238	Glasgow Combined Aircraft/Road Traffic Survey (1984)	
Railway		
FRA-063	Paris Area Railway Noise Survey (1972)	*
GER-192	German Road/Railway Noise Comparison Study (1978/1981)	
NET-153	Netherlands Railway Noise Survey (1977)	
NET-276	Netherlands Tram and Road Traffic Noise Survey (1983)	
NET-361	Netherlands Environmental Pollution Annoyance Survey (1993)	NA
SWE-165	Gothenburg Tramway Noise Survey (1976)	*
SWE-228	Swedish Railway Study (1978–1980)	*
SWE-365	Swedish 15-site Railway Study (1992–1993)	
UKD-116	British National Railway Noise Survey (1975/1976)	

Data sets as in Miedema and Vos (*5*), except for NET-361, which was not used here (NA) because the number of cases was too small for the analyses in this paper; some minor corrections have been applied (*15*). For each data set, it is indicated how DENL is established. If this was done directly from the basic L_{Aeq} data, there is a blank in the determination column.
*Indicates that the rules from the Appendix have been used. For three airports in AUL-210, the specific rules used are given (see text).

Exposure–Response Model

Basic model. The noise annoyance of an individual on a scale from 0 to 100 is denoted by A^*. Instead of observing A^* precisely, we only know the interval in which A* comes on the scale for an individual. The locations of the boundaries of the intervals depend on the set of annoyance response categories used in a study.

On the basis of Miedema (*10*), where a linear relationship between DNL and A^* was found, A^* is assumed to be the sum of two components—namely, a component that is a linear function of DNL (or DENL) and a random component. Thus:

$$A^* = \beta_0 + \beta_1 \mathrm{DNL} + \varepsilon^* \qquad [1]$$

Here β_0 is the intercept, β_1 is the slope coefficient of DNL, and ε^* is the random component. The random component, ε^*, and hence A^*, is assumed to have a censored normal distribution. {A random variable X with bounded support $[\tau_L,\tau_R]$ has a censored normal distribution with parameters μ, σ, τ_L, and τ_R [the left and right censoring points] if its density equals $\phi[(x-\mu)/\sigma]$ for $x \in\,]\tau_L\ \tau_R[$ and if at the censoring points $P(X = \tau_L) = \Phi[(\tau_L - \mu)/\sigma]$ and $P(X = \tau_R) = 1 - \Phi[(\tau_R - \mu)/\sigma]$. $\Phi(x)$ represents the cumulative standard normal distribution and $\phi(x)$ the standard normal density.} This means that there is a normally distributed variable A such that A^* equals A if $A \in [0,100]$, $A^* = 0$ if $A < 0$, and $A^* = 100$ if $A > 100$. The reason for assuming a censored normal distribution is as elaborated below.

A^* has values in the interval [0,100] so that its distribution has bounded support. The dispersion of A^* varies with the noise exposure: for low DNL levels (just above 45 dB) and high levels of DNL (just below 75 dB), the annoyance varies less among people than at intermediate values of DNL. A distribution that has both characteristics (bounded support on [0,100] and a variation related to DNL as described) is a censored normal distribution with the mean increasing as a function of DNL. Therefore the distribution of ε^*, and hence A^*, is assumed to be censored normal.

Instead of considering A^*, it is more convenient to model the corresponding, normally distributed variable A. Then the model is

$$A = \beta_0 + \beta_1 \mathrm{DNL} + \varepsilon, \qquad [2]$$

where ε is normally distributed with zero mean and constant variance σ^2, that is, $\varepsilon \sim N(0, \sigma^2)$. The parameters of Equation 2 can be estimated with grouped regression analysis (*11*) if only the interval in which A comes is observed.

A common type of measure of annoyance is the percentage of people whose annoyance exceeds a certain annoyance level *C*. This is the main descriptor of the annoyance distribution of interest. The probability, p_C(DNL), that someone with exposure DNL has an annoyance level that exceeds *C* is

$$\begin{aligned} p_C(\mathrm{DNL}) &= Prob\ (A \geq C) \\ &= Prob\ (\beta_0 + \beta_1 \mathrm{DNL} + \varepsilon \geq C) \\ &= Prob\ (\varepsilon \geq C - \beta_0 - \beta_1 \mathrm{DNL}) \\ &= 1 - \Phi\ [(C - \beta_0 - \beta_1 \mathrm{DNL})/\sigma], \end{aligned} \quad [3]$$

where Φ represents the cumulative standard normal distribution. [The standard normal distribution $\Phi(x)$ equals $(2\pi)^{-1/2} \int \exp(-0.5 \times t^2)\ dt$, with integration over the interval minus infinity to *x*.]

The annoyance distribution can be fully described by varying *C* and calculating p_C(DNL) for each *C*. Given estimates b_0, b_1 of the intercept β_0 and the slope β_1, and estimate *s* of the standard error σ, respectively, then

$$\hat{p}_C\ (DNL) = 1 - \Phi\left(\frac{C - b_0 - b_1 DNL}{s}\right)$$

is an estimate of p_C(DNL). Then 100 × $\hat{p}_C$(DNL) is an estimate of the percentage of persons with noise exposure DNL whose annoyance exceeds *C*. In the "Results" section, results will be presented for three different values for *C*: 28 (little annoyed), 50 (annoyed), and 72 (highly annoyed). In addition, the estimates of the parameters will be presented so that the percentage of persons with a certain DNL whose annoyance exceeds *C* can be calculated for any *C*.

Extended model. In standard regression models it is assumed that individuals have been drawn at random from a population and that the random components, ε, for the individuals are independent. However, the individuals in the present multistudy data set are not drawn at random, but can be thought of as having been drawn in clusters defined by the studies. If there is a study effect and the study level in the sample is ignored, then estimates of standard errors are biased (too low). Underestimated standard errors result in too-narrow confidence intervals. The underestimation depends on the size of the study effect. Because there is a large study effect in noise annoyance investigations, it is important to take this aspect of the data set into account. An accepted method of incorporating study effects is formulating a multilevel model (*12*). A multilevel version of models such as Equation 2, of which the parameters can be estimated by grouped regression, has been studied by Keen and Engel (*13*).

Including a study effect on the intercept of the relationship specified in Equation 2 gives (using individual index *i* and study index *j*)

$$A_{ij} = \beta_0 + \beta_1 DNL_{ij} + u_{0j} + \varepsilon_{ij}, \quad [4]$$

where u_{0j} is a random study factor, normally distributed with zero mean and variance σ_0^2. According to this model the relation between DNL and annoyance can have a different intercept in each study. The average intercept is equal to β_0. The total random component in Equation 4 is equal to $u_{0j} + \varepsilon_{ij}$. This means that the observations within one study are not independent.

Using Equation 4, the probability that a randomly selected person from a randomly selected study, with exposure level DNL, has an annoyance level that exceeds *C* [i.e., p_C(DNL)], can be estimated as follows.

The probability conditional on the random study factor u_0 is

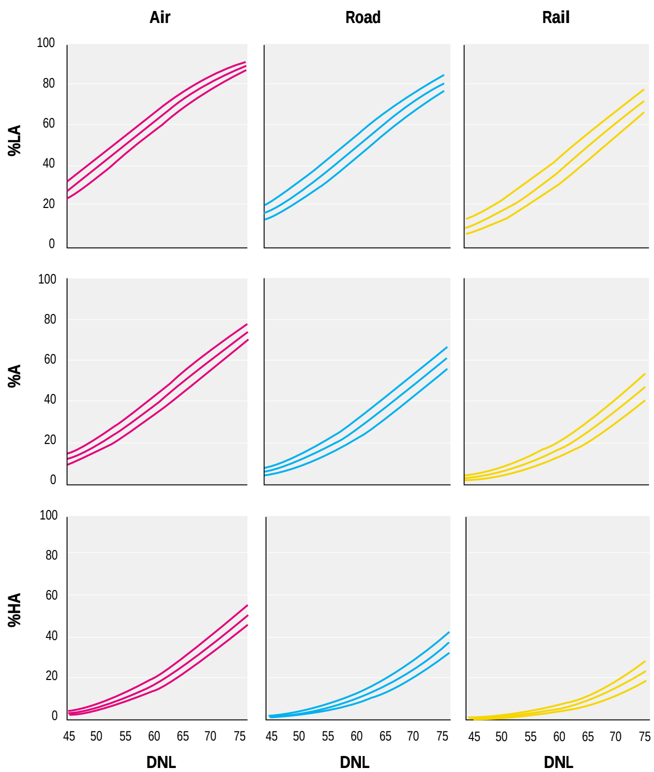

Figure 1. The %LA (top row), %A (middle row), and %HA (bottom row) for aircraft, road traffic, and railways as a function of DNL, together with 95% confidence intervals. The curves were found by fitting Equation 4 to the data from field surveys (see Table 2). The estimates of the parameters are given in Table 3.

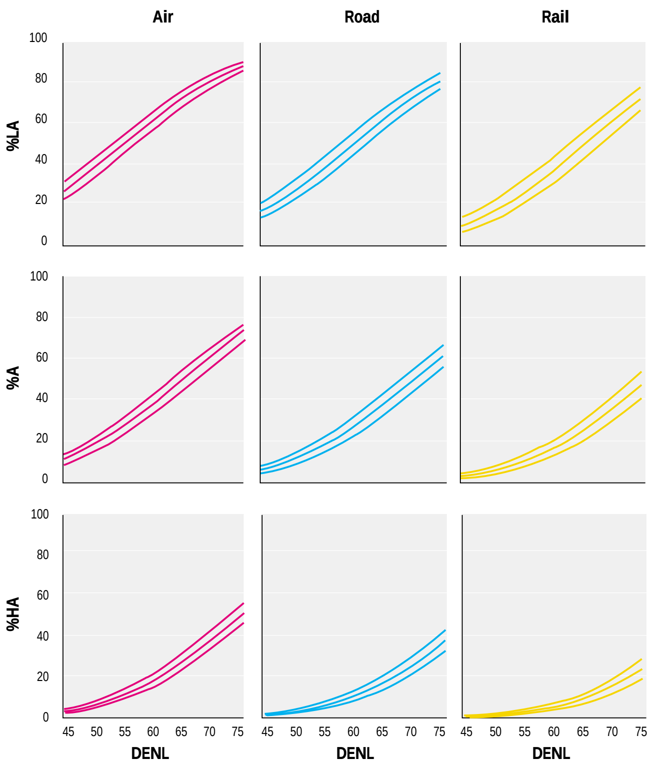

Figure 2. The %LA (top row), %A (middle row), and %HA (bottom row) for aircraft, road traffic, and railways as a function of DENL, together with the 95% confidence intervals. The curves were found by fitting Equation 4 to the data from field surveys (see Table 2). The estimates of the parameters are given in Table 4.

$$p_C(\text{DNL}|u_0) = Prob(A \geq C\,|u_0) = Prob(\varepsilon \geq C - \beta_0 - \beta_1\text{DNL} - u_0|u_0).$$

Using this and the assumption that u_0 is normally distributed with mean zero and variance σ_0^2, the following result can be obtained:

$$p_C(DNL) = Prob\left(\beta_0 + \beta_1 DNL + u_{0j} + \varepsilon \geq C\right) = 1 - \Phi\left(\frac{C - \beta_0 - \beta_1 DNL}{\sqrt{\sigma^2 + \sigma_0^2}}\right) \qquad [5]$$

The term $\sigma^2 + \sigma_0^2$ in Equation 5 has the same role as σ^2 in Equation 3.

To estimate the probability that the annoyance level of a randomly selected person from a randomly selected study exceeds C, the four parameters β_0, β_1, σ_0^2, and σ^2 must be estimated. Standard grouped regression analysis could not be used because this assumes independence of the random components. We used SAS PROC NLMIXED (SAS version 8, SAS Institute, Cary, NC, USA) to obtain the estimates, because with this procedure the study effect could be properly taken into account.

Given the estimates b_0, b_1, s_0^2, and s^2 of β_0, β_1, σ_0^2 and σ^2, respectively, the expected percentage of persons with noise exposure DNL whose annoyance exceeds C can be estimated as follows:

$$100 \times \hat{p}_C(DNL) = 100\left[1 - \Phi\left(\frac{C - b_0 - b_1 DNL}{\sqrt{s^2 + s_0^2}}\right)\right] \qquad [6]$$

Confidence intervals. This subsection explains how the confidence intervals are calculated. The reader who is not mathematically trained may want to skip this subsection.

Let x be the transpose of the vector (1, DNL) [i.e., $(1, \text{DNL})^t$] with DNL a certain noise level. Let Σ_β denote the covariance matrix of the coefficients β_0 and β_1. Furthermore, b is the vector of estimates $(b_0, b_1)^t$. Then the 95% lower and upper confidence limits of the expected annoyance at exposure level DNL are

$$C_{L,U} = x^t b \pm 1.96\sqrt{\left(x^t S_b x\right)} \qquad [7]$$

The confidence limits for p_C(DNL) are

$$1 - \Phi\left(\frac{C - C_{L,U}}{\sqrt{s^2 + s_0^2}}\right),$$

where s is an estimate of σ, s_0 is an estimate of σ_0, and $C_{L,U}$ is given by Equation 7.

Results

The Model in Equation 4 was fitted separately for aircraft, road traffic, and railways because earlier analyses demonstrated significant differences between the relationships for these types of sources (*5*). Figure 1 (for DNL) and Figure 2 (for DENL) show the percentage of persons who are (at least) a little annoyed (annoyance ≥ 28), annoyed (annoyance ≥ 50), and highly annoyed (annoyance ≥ 72). In addition to the curves, the corresponding confidence intervals are also shown. The estimates of the coefficients β_0, β_1, σ_0^2, and σ^2 for aircraft, road traffic, and railways are presented in Table 3 (for DNL) and Table 4 (for DENL) with their estimated standard errors and significance levels. Comparing the estimates of σ_0^2 and σ^2 shows that there is a significant between-study variation for aircraft and road traffic, but the within-study variation is much larger. The order of magnitude of the within-study variation, and hence of the total variation, is equal for aircraft, road traffic, and railways.

The obtained curves can be approximated accurately with third-order polynomials using source-independent exposure values for zero %LA (namely, 32 dB), %A (namely, 37 dB), and for %HA (namely, 42 dB). Approximations for DNL are presented in Table 5.

Figures 3 (DNL) and 4 (DENL) show that the approximations are almost equal to the estimated curves. Curves for other annoyance cutoff points, C, can be obtained by substituting the chosen C and the estimates of the coefficients (Tables 3 and 4) in Equation 6.

An alternative to measures such as %LA, %A, and %HA is the mean annoyance. For establishing the mean annoyance as a function of DNL or DENL, it is important to note that the estimated annoyance distribution is non-zero outside the interval [0,100], whereas the actual annoyance scores are restricted to that interval. Consequently, it is not the mean of the estimated normal annoyance distribution, but the mean of the corresponding censored normal distribution, that is an estimate of the mean annoyance observed with a scale from 0 to 100.

Discussion and Conclusion

We presented a model of the distribution of noise annoyance with the mean varying as a function of the noise exposure; DNL and DENL were used as noise descriptors.

Table 3. The estimated coefficients of Equation 5 using DNL as noise exposure metric for aircraft, road traffic, and railways separately.

Parameter	Estimate	SE	*p*-Value
Aircraft (27,081 observations; 19 studies)			
β_0	–89.67	3.30	< 0.0001
β_1	2.16	0.0406	< 0.0001
σ_0^2	81.05	26.93	0.0075
σ^2	1185.90	20.11	< 0.0001
Road traffic (19,172 observations; 26 studies)			
β_0	–105.72	3.89	< 0.0001
β_1	2.21	0.0473	< 0.0001
σ_0^2	150.32	42.93	0.0018
σ^2	1150.08	18.65	< 0.0001
Railways (7,632, observations; 8 studies)			
β_0	–107.45	6.16	< 0.0001
β_1	2.06	0.0819	< 0.0001
σ_0^2	51.01	26.90	0.0998
σ^2	1043.43	44.32	< 0.0001

Table 4. The estimated coefficients of Equation 5 using DENL as noise exposure metric for aircraft, road traffic, and railways separately.

Parameter	Estimate	SE	*p*-Value
Aircraft (27,081 observations; 19 studies)			
β_0	–91.42	3.30	< 0.0001
β_1	2.17	0.0407	< 0.0001
σ_0^2	77.64	25.83	0.0076
σ^2	1187.11	20.13	< 0.0001
Road traffic (19,172 observations; 26 studies)			
β_0	–106.97	3.91	< 0.0001
β_1	2.22	0.0476	< 0.0001
σ_0^2	150.54	42.99	0.0018
σ^2	1150.71	18.66	< 0.0001
Railways (7,632 observations; 8 studies)			
β_0	–110.09	6.33	< 0.0001
β_1	2.10	0.0840	< 0.0001
σ_0^2	53.86	28.55	0.1013
σ^2	1078.73	47.21	< 0.0001

Because the entire annoyance distribution has been modeled, any annoyance measure that summarizes this distribution can be calculated from the model. The model has been fitted to data from noise annoyance studies for aircraft, road traffic, and railways separately. Polynomial approximations of relationships implied by the model for combinations of exposure and annoyance measures were presented. These approximations are easier to use for practical calculations than the model itself because the model involves a normal distribution.

The present results are based on the same data set that was previously used to establish relationships between DNL and %HA (*5*). In this paper we provide better estimates of the confidence intervals due to the improved model of the relationship between annoyance and noise exposure. Moreover, relationships using descriptors other than DNL and %HA, which are presented here, have not been established earlier on the basis of a large data set. The predictability of the annoyance of the general population exposed to a certain noise level (DNL or DENL) is quantified by the width of the confidence interval at that noise level for the noise and annoyance measure concerned.

The exposure–response functions and their curves presented here are only to be used for aircraft, road traffic, and railway noise. The curves are not necessarily valid for specific sources such as helicopters, low-flying military aircraft, train shunting noise, shipping noise, or aircraft noise on the ground. The curves were derived for adults on the basis of surveys distributed over countries as shown in Table 2. On the basis of inspection of the curves presented earlier (*5*), we hypothesize that there are no important differences between countries in the reaction of the population to similar noise exposures, but this needs to be investigated further.

The validity of the presented curves depends to a large extent on the validity of the data used. The model of annoyance as a function of noise exposure (described by DNL or DENL) was fitted to the data from a large set of field studies in which noise exposure and noise annoyance were determined. For most other environmental pollutants, the situation is less favorable because only data from animal studies are available, which must be extrapolated to humans. This extrapolation involves strong assumptions regarding the relation between effects in animals and effects in humans and strong assumptions regarding the relation between effects of high exposures in a relatively short time interval in the laboratory and effects of long-term low exposures in real life. Such assumptions were not necessary here because noise annoyance was studied extensively, directly with humans in the relevant exposure situations. There are few environmental pollutants, if any, for which there is such an extensive set of valid data for deriving exposure–response relationships or thresholds.

The noise annoyance curves that have been found have rather narrow confidence intervals. This means that the location of these curves in the population is known rather accurately. Nevertheless, substantial deviations from the predicted distribution of annoyance responses for limited groups at individual sites must be expected because random factors, individual and local circumstances, and study characteristics affect the noise annoyance.

However, in many cases the prediction on the basis of a norm curve that is valid for the entire population is a more suitable basis for policy than the actual annoyance of a particular individual or group. For example,

Table 5. Approximations for DNL and DENL.

Measure/source	DNL	DENL
%LA		
Aircraft	-5.741×10^{-4} (DNL – 32)^3 + 2.863×10^{-2} (DNL – 32)^2 + 1.912 (DNL–32)	-6.158×10^{-4} (DENL – 32)^3 + 3.410×10^{-2} (DENL – 32)^2+ 1.738 (DENL – 32)
Road traffic	-6.188×10^{-4} (DNL – 32)^3 + 5.379×10^{-2} (DNL – 32)^2 + 0.723 (DNL–32)	-6.235×10^{-4} (DENL – 32)^3 + 5.509×10^{-2} (DENL – 32)^2+ 0.6693 (DENL – 32)
Railways	-3.343×10^{-4} (DNL – 32)^3 + 4.918×10^{-2} (DNL – 32)^2 + 0.175 (DNL–32)	-3.229×10^{-4} (DENL – 32)^3 + 4.871×10^{-2} (DENL–32)^2 + 0.1673 (DENL – 32)
%A		
Aircraft	1.460×10^{-5} (DNL – 37)^3 + 1.511×10^{-2} (DNL – 37)^2 + 1.346 (DNL–37)	8.588×10^{-6} (DENL – 37)^3 + 1.777×10^{-2} (DENL–37)^2 + 1.221 (DENL – 37)
Road traffic	1.732×10^{-4} (DNL – 37)^3 + 2.079×10^{-2} (DNL – 37)^2 + 0.566 (DNL–37)	1.795×10^{-4} (DENL – 37)^3 + 2.110×10^{-2} (DENL–37)^2 + 0.5353 (DENL – 37)
Railways	4.552×10^{-4} (DNL – 37)^3 + 9.400×10^{-3} (DNL – 37)^2 + 0.212 (DNL–37)	4.538×10^{-4} (DENL – 37)^3 + 9.482×10^{-3} (DENL–37)^2 + 0.2129 (DENL – 37)
%HA		
Aircraft	-1.395×10^{-4} (DNL – 42)^3 + 4.081×10^{-2} (DNL – 42)^2 + 0.342 (DNL–42)	-9.199×10^{-5} (DENL – 42)^3 + 3.932×10^{-2} (DENL–42)^2 + 0.2939 (DENL – 42)
Road traffic	9.994×10^{-4} (DNL – 42)^3 – 1.523×10^{-2} (DNL – 42)^2 + 0.538 (DNL–42)	9.868×10^{-4} (DENL – 42)^3 – 1.436×10^{-2} (DENL–42)^2 + 0.5118 (DENL – 42)
Railways	7.158×10^{-4} (DNL – 42)^3 – 7.774×10^{-3} (DNL – 42)^2 + 0.163 (DNL–42)	7.239×10^{-4} (DENL – 42)^3 – 7.851×10^{-3} (DENL–42)^2 + 0.1695 (DENL – 42)

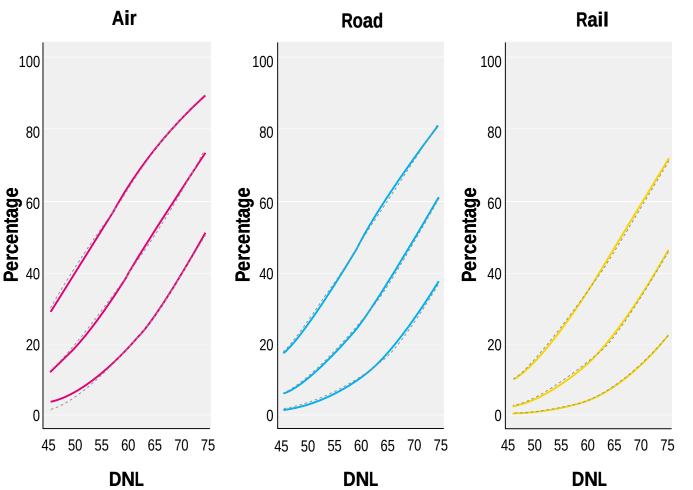

Figure 3. The estimated curves (solid lines) and their polynomial approximations (dashed lines) for DNL.

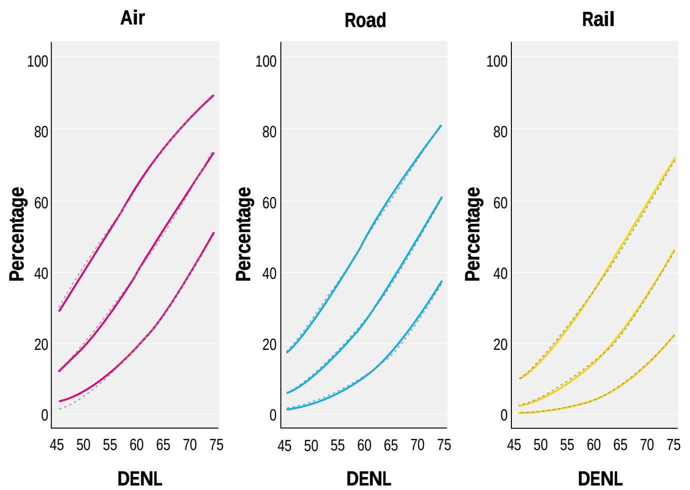

Figure 4. The estimated curves (solid lines) and their polynomial approximations (dashed lines) for DENL.

a norm curve is useful when exposure limits for dwellings and noise abatement measures are discussed. Equity and consistency require that limits and abatement measures do not depend on the parculiarities of the persons and their actual circumstances. For similar reasons, a norm curve also can be used to estimate the number of highly annoyed persons in the vicinity of an airport, road, or railway when different scenarios concerning extension of these activities or emission reductions, for example, are to be compared. That the norm curve does not take local circumstances or reactions to a change in exposure itself into account is considered advantageous for many purposes. Equity and consistency of policy would not be served if in each case the actual annoyance is taken as the only basis for these evaluations.

The above concept of equity stresses the acceptance of equal exposures for all individuals. This kind of equity is generally strived for in environmental protection. After limits have been established on the basis of studies among the general population or a sensitive group, they are applied to any specific population irrespective of the match between that specific population and the study population. Nonetheless, another form of equity that stesses equal tolerance with respect to the individual effect may be useful in certain circumstances. At the local level measures may be taken on the basis of the actual, individual response to the noise exposures. A survey is needed to obtain insight in such place- and time-bound responses.

To put it in another way, the exposure–response functions and their curves can be used for strategic assessment. They can be

Appendix

Relation between DENL and DNL

Expectations regarding DENL – DNL on the basis of time patterns. DNL has been used as the noise metric (*5*). Here general rules are derived for translating DNL into DENL. These general rules are used in the analyses in this paper only if DENL could not be determined on the basis of (estimates of) the L_{Aeq} in terms of which DENL is defined.

There is no consistent relation between DNL and DENL. The difference between the two metrics depends on the time pattern of the noise exposure. The possible differences are restricted if it is assumed that the noise level does not increase during the evening and the night; more specifically, if L_{Aeq}(0700–1900 hr) ≥ L_{Aeq} (1900–2200 hr) ≥ L_{Aeq}(2200–2300 hr) ≥ L_{Aeq}(2300–0700 hr). This assumption will hold for the vast majority of situations.

Assuming a decreasing pattern of L_{Aeq} as described above, the lowest value of DENL – DNL is equal to –0.06 dB. This means that it can be stated without significant error that DENL – DNL ≥ 0. The highest value of DENL – DNL occurs if the (hourly) L_{Aeq} remains constant until 2200 hr and drops sharply at 2200–2300 hr (and thereafter). Assuming the above described decreasing pattern of L_{Aeq}, the maximum value DENL – DNL is equal to 1.56 dB. On the basis of these findings it can be roughly stated that the range of the difference DENL – DNL is 0–1.5 dB. To get a more detailed insight, the difference DENL – DNL has been calculated for various combinations of positive differences between the L_{Aeq} for the successive time intervals: L_{Aeq}(0700–1900 hr) – L_{Aeq}(1900–2200), L_{Aeq}(1900–2200 hr) – L_{Aeq}(2200–2300 hr), and L_{Aeq}(2200–2300) – L_{Aeq}(2300–0700 hr). The calculations indicated that both a constant (hourly) L_{Aeq} until 2200 hr and a sharp decrease at 2200–2300 hr are necessary conditions for a value of DENL – DNL that is substantially larger than 0.

Because different noise sources have to some extent a typical time pattern, the range 0–1.5 dB can be further restricted for a specific type of noise source. In general, the (hourly) L_{Aeq} caused by trains will not change much until after 2300 hr. For trams there may be a decrease in the evening, but in general there is no sharp decrease between 2200 and 2300 hr. This means that railway noise generally does not fullfill the two requirements for a significant value of DENL – DNL [stability of the (hourly) L_{Aeq} until 2200 hr and a sharp decrease at 2200–2300 hr]. Therefore, this difference will be close to zero for railway noise.

In general, the road traffic noise level gradually decreases during the evening, and this decrease often is accelerated in the period 2100–2400 hr. The decrease in the noise level at 2200–2300 hr will in general be smaller than 3 dB. The larger this decrease at 2200–2300 hr, the larger the decrease of the level in the preceding period of the evening will be. Assuming this, the above-mentioned calculations indicate that for road traffic noise DENL – DNL will generally be < 0.5.

For aircraft noise there may be a sharp decrease of the noise level, depending on the operation of the airport. Little can be said about the consequence for the value of DENL – DNL. If a sharp decrease occurs at 2200–2300 hr, then this difference may be 1 dB, but the conditions needed for a value of the difference up to 1.5 dB are not generally expected.

Empirical data regarding DENL – DNL. The table below gives an overview of the studies in the TNO archive of noise annoyance studies that contain estimates of (the L_{Aeq} needed to determine) both DENL and DNL. Inspection of scatter plots with DENL and DNL on the axes showed that the data points lie close to the line DENL = DNL and that the small deviations from that line are not level dependent. Therefore, the relation between DENL and DNL is summarized in Table A1 by the average value per data set for the difference DENL – DNL. The values for the average in Table A1 confirm the previous analysis on the basis of the time pattern; that is, the average for railways nearly equals zero, the averages for road traffic are slightly larger but also close to zero, while the averages for aircraft noise are larger and vary.

Conclusion. On the basis of the expectations derived from the time patterns of the noise level and the available relevant empirical evidence, we conclude that the following equations can be used to transform the DNL of a noise exposure into DENL:

Aircraft DENL = DNL + 0.6

Road traffic DENL = DNL + 0.2

Railway DENL = DNL

These are general rules that do not necessarily give the precise relationship between the two noise metrics for an individual case. However, the analysis of the time pattern of the noise level indicates that values of the difference DENL – DNL outside the range 0–1.5 dB will be rare.

Table A1. Difference between DENL and DNL found for various studies.

Fields' code (*6*)	DENL – DNL	*n*
Aircraft		
FRA-239	1.5	565
NET-240	0.6	573
NET-371	0.6	11,211
UKD-238	0.5	598
Road traffic		
FRA-239	0.2	524
GER-192	0.1	893
JPN-369	0.1	823
NET-106	0.1	420
NET-240	0.2	473
NET-258	0.1	365
NET-362	0.2	293
SWI-173	0.2	1,371
TRK-367	0.2	154
UKD-238	0.3	536
Railway		
GER-192	–0.1	966

used in target setting, in translating noise maps into overviews of numbers of persons annoyed, in cost–benefit analyses, and in environmental health impact assessments. When used in environmental health impact assessments, they give insight to the situation that is expected in the long term. They are not applicable to local, complaint-type situations or to the assessment of the short-term effects of a change of noise climate. With the present state of the art, the annoyance in those cases can be assesessed only by conducting a noise annoyance survey in the situation concerned.

In principle, the estimation of the curves and their confidence intervals can be further elaborated by incorporating study site as an extra level in the analysis. In most studies, a limited number of study sites were selected first, and then respondents were selected at random at each site. Because it is likely that site characteristics other than the noise exposure levels at the site affect the annoyance, incorporating the sites as an extra level in the analysis would be an improvement. A site level was not included in the present analyses because the available data sets do not contain comparable definitions of sites.

Another, more important elaboration of the present model would be the inclusion of more (exposure) variables as predictors of annoyance, in addition to DNL or DENL (at the most exposed side of a dwelling). Most interesting are factors that can be influenced by policy. Examples of such factors are the sound insulation of the dwelling and the presence of a relatively quiet side of the dwelling. The latter factor depends on the configuration and orientation of the building relative to the noise source. The purpose then would be to establish a model of the annoyance reactions in the population as a function of DNL or DENL, the sound insulation of the dwelling, and the level at the most quiet side of the dwelling.

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