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1 Introduction

The last decade TNO in Leiden has built an archive of original datasets from studies on annoyance caused by environmental noise. Investigations on different modes of transportation (aircraft, road traffic, and railway) are included. They were carried out in Europe, North America, and Australia. As far as possible a common set of variables has been derived from the studies, which includes, among others, noise exposure measures, noise annoyance measures, and various demographic and attitudinal variables. Much effort has been put into the consistent derivation of the common variables from different studies. Studies are included in the archive if and only if a noise measure (DNL or L_{Aeq}(24h)) and the percentage highly annoyed persons (%HA) can be derived in such a way that they satisfy certain minimal criteria (see Miedema and Vos, 1998).

Miedema and Vos (1998) used the above database to derive synthesis curves for the relationship between DNL and percentage highly annoyed for aircraft, road traffic, and railway noise (DNL - %HA curves). These curves are based on all 21 datasets examined by Schultz (1978) and Fidell, Barber, and Schultz (1991) for which acceptable DNL and percentage highly annoyed measures could be derived, augmented with 34 datasets. Separate, non-identical curves were found for aircraft, road traffic, and railway noise. This report gives in addition to these curves also synthesis curves for the relationship between DNL and annoyance score for the three transportation noise sources (DNL – A curves). Earlier such curves have been derived on the basis of a subset of the present database (Miedema and Vos, 1992; Miedema, 1993). This report also discusses impulsive noise and other noise from stationary sources.

2 Data

Table 1 gives an overview of the datasets on which the DNL - %HA curves in Miedema and Vos (1998) were based. Each dataset is identified by its code from Fields' catalogue of noise annoyance surveys (Fields, 1994). The 55 datasets used to derive the curves published in 1998 encompass information for a total of 63 969 respondents (counting respondents twice if they appear in two datasets). The datasets were derived from 45 surveys with a total of 58 065 respondents. Only respondents for whom DNL and an annoyance response are available are counted. Extreme exposure levels (< 45 and > 75 dB) were excluded from the analyses in which the synthesis curves were established. This reduced the number of respondents considerably, namely to 55 575 respondents (counting respondents twice if they appear in two datasets). The number of respondents per type of source are as follows: aircraft 28 030, road traffic 19 679, railway 7 866).

The dataset used in the present analysis is slightly different from the one used in Miedema and Vos (1998) because of the following three reasons.

- One very small dataset (NET-361, 71 cases) has been deleted because inclusion leads to violation of the assumption that the effect of study type on the exposure response curves has a normal distribution (see section 4). The procedure MIXED with method MIVQUE0 in the SAS package (SAS Intitute Inc, 1996), which was used to find the model parameters, is not robust against strong violations of the normality assumptions. The procedure (RE)ML is robust but this iterative procedure did not converge for all analyses.

- Furthermore, the selection of the respondents whose LDN come into the range 45 – 75 dB is now done on the basis of the individual exposure levels, if available, while previously respondents were selected after they were clustered in DNL classes.

- Finally, two errors in one dataset (USA-204), which was conducted in four rounds in three neighbourhoods, have been corrected. Now the respondents from the three neighbourhoods in the first round were selected, while previously the respondents from the four rounds in one neighbourhood had been selected. Furthermore, the proportions of respondents per annoyance category given by Fidell et al. (1985: table IV) were found not to add to 1, presumably because also the respondents who did not give an answer were included in the total on the basis of which proportions were calculated (personal communication with S. Fidell, 2 – 3 Sept 1999). Now the proportions were recalculated on the basis of the number of respondents who gave an answer.

The number of respondents within the range 45 – 75 dB that resulted after these adaptations are given per study in table 1. The effect of these adaptations on the DNL - %HA curve is very small, as will be shown in section 5.

For most datasets in table 1 not only the percentage highly annoyed (%HA) can be determined, but also other noise annoyance measures such as the annoyance score (A). These datasets contained either the individual responses or the distribution of the responses over the annoyance categories per group of respondents with similar DNL. The datasets that contained insufficient information to derive the additional annoyance measures are marked with an asterix in table 1.

Table1 Datasets on which the DNL - %HA curves are based. The DNL – A lines are based on the datasets not marked with an asterix.

Aircraft		
Fields' code	Name of the survey	Number of respondents (for this source)
AUL-210	Australian Five Airport Survey (1980)	3208
CAN-168	Canadian National Community Noise Survey (1979)	631
FRA-016	French Four-Airport Noise Study (1965)	1300
FRA-239	French Combined Aircraft/Road Traffic Survey (1984)	565
NET-240	Schiphol Combined Aircraft/Road Traffic Survey (1984)	573
NOR-311	Oslo Airport Survey (1989)	1396
NOR-328	Bodo Military Aircraft Exercise Study(1991-1992)	673
NOR-366	Vaernes Military Aircraft Exercise Study(1990-1991)	321
SWE-035*	Scandinavian Nine-Airport Noise Study (1969, 1970, 71,72, 74,76)	1491
SWI-053	Swiss Three-City Noise Survey (1971)	3076
UKD-024	Heathrow Aircraft Noise Survey (1967)	3845
UKD-242	Heathrow Combined Aircraft/Road Traffic Survey (1982)	1993
UKD-238	Glasgow Combined Aircraft/Road Traffic Survey (1984)	598
USA-022	U.S.A. Four-Airport Survey (phase I of Tracor Survey) (1967)	2235
USA-032	U.S.A. Three-Airport Survey (phase II of Tracor Survey) (1969)	1491
USA-044	U.S.A. Small City Airports (small City Tracor Survey) (1970)	1612
USA-082	LAX Airport Noise Study (1973)	374
USA-203	Burbank Aircraft Noise Change Study (1979)	586
USA-204	John Wayne Airport Operation Study (1981)	602
USA-338*	U.S.A. 7-Air Force Base Study (1981)	839
	Total Aircraft (20 datasets)	27 409

(Table 1 continued)

Road Traffic		
Fields' code	Name of the survey	Number of respondents (for this source)
CAN-120	Western Ontario University Traffic Noise Survey (1975)	1112
CAN-121	Southern Ontario Community Survey (1975/1976)	1147
CAN-168	Canadian National Community Noise Survey (1979)	568
BEL-122*	Antwerp Traffic Noise Survey (1975)	836
BEL-137*	Brussels Traffic Noise Survey (1976)	228
FRA-092	French Ten-City Traffic Noise Survey (1973/1975)	879
FRA-239	French Combined Aircraft/Road Traffic Survey (1984)	524
FRA-364	French 18-site Time of Day Study (1993/1994)	848
GER-192	German Road/Railway Noise Comparison Study (1978/1981)	1577
GER-372	Ratingen-Dusseldorf Road Traffic/Aircraft Survey (1985/1986)	546
GER-373	Ratingen Road Traffic/Aircraft Study (1987)	421
NET-106	Dordrecht Home Sound Insulation Study (1974)	420
NET-240	Schiphol Combined Aircraft/Road Traffic Survey (1984)	473
NET-258	Amsterdam Home Sound Insulation Study (1975)	304
NET-276	Netherlands Tram and Road Traffic Noise Survey (1993)	697
NET-361	Netherlands Environmental Pollution Annoyance Survey (1983)	788
NET-362	Arnhem Road Traffic Study (1984)	293
SWE-142*	Stockholm, Visby, Gothenburg Traffic Noise Study (1976)	675
SWE-165	Gothenburg Tramway Noise Survey (1976)	464
SWI-053	Swiss Three-City Noise Survey (1971)	945
SWI-173	Zurich Time-of Day Survey (1978)	1219
UKD-071	B.R.S. London Traffic Noise Survey (1972)	2058
UKD-072	English Road Traffic Survey (1972)	902
UKD-157	London Area Panel Survey (1977/1978)	302
UKD-242	Heathrow Combined Aircraft/Road Traffic Survey (1982)	410
UKD-238	Glasgow Combined Aircraft/Road Traffic Survey (1984)	528
	Total Road Traffic (26 datasets)	19 164
Railway		
Fields' code	Name of the survey	Number of respondents (for this source)
FRA-063	Paris Area Railway Noise Survey (1972)	82
GER-192	German Road/Railway Noise Comparison Study (1978/1981)	1566
NET-153	Netherlands Railway Noise Survey (1977)	602
NET-276	Netherlands Tram and Road Traffic Noise Survey (1983)	265
SWE-165*	Gothenburg Tramway Noise Survey (1976)	464
SWE-228*	Swedish Railway Study (1978-1980)	754
SWE-365	Swedish 15-site Railway Study (1992-1993)	2802
UKD-116	British National Railway Noise Survey (1975/1976)	1087
	Total Railway (9 datasets)	7622

3 DNL, % HA, AND A

DNL is a measure with a night-time penalty of 10 dB calculated from L_{Aeq} for the daytime and L_{Aeq} for the night-time:

$$DNL = 10 \lg (15.10^{Ld/10} + 9.10^{(Ln + 10)/10})/24.$$

Here Ld = L_{Aeq}(7-22h) and Ln = L_{Aeq}(22-7h). The L_{Aeq}'s are measured, or calculated with noise propagation models. As much as possible we derived the L_{Aeq}'s for the incident sound at the most exposed facade of a dwelling for the one year period preceding a social survey. However, it is not a common practice to report information on these aspects of the determination of L_{Aeq}, so that often they were unknown.

The annoyance score A is obtained by assigning numbers to annoyance categories. A typical noise annoyance question is: "How would you describe your general feelings about the aircraft noise in this neighbourhood? Would you say you are: (1) not at all annoyed (2) slightly annoyed (3) moderately annoyed, (4) considerably annoyed, or (5) highly annoyed?" On the basis of the assumption that each category of this 5-point category scale occupies an equal portion of the annoyance continuum the midpoints 10, 30, 50, 70, and 90 of five categories from 0 to 100 are assigned as scores to these categories. Scores are assigned in a similar manner if a different number of categories is used. The general rule is:

$$\text{score}_{\text{category } i} = 100\,(i - ½)\,/\,m,$$

where m is the number of categories and i = 1,..,m is the rank number of the category. For corrections because of expected effects of specific, unusual verbal category labels used in some studies, see Miedema and Vos (1998).

%HA is the percentage of annoyance responses exceeding a certain cut-off point. To assess the percentage above a cut-off point the boundaries of annoyance categories must be quantified. A boundary quantification is determined as follows:

$$\text{score}_{\text{boundary } i} = 100\, i\,/\,m,$$

where m is the number of effective categories and i = 0,1,..,m is the rank of the boundary, starting with the lower boundary of the lowest annoyance category.
To arrive at a percentage responses above a cut-off point x, a score is assigned to each respondent in the following way. Let L and U be the quantifications of the lower and the upper boundary of the category selected by a respondent. Then the score assigned to the respondent for the calculation of the percentage is 0 if the respondent chose a category that is below the cut-off point x (i.e., $U < x$) and is 1 if the respondent chose a category that is above the cut off point x (i.e., $x \leq L$). If the category chosen by the respondent encompasses the cut-off point (i.e., $L < x \leq U$), then it is

not known whether this is a response below or above the cut-off point. The score assigned to these respondents is the probability that the annoyance score for the respondent actually is above the cut-off point, assuming that the annoyance score is uniformly distributed within a category. The percentage obtained with 72 as the cut-off point is called the percentage 'highly annoyed'. The interpretation of a percentage does not depend on this label, but on the value chosen as the cut-off point, i.e. 72. An advantage of using a cut-off at 72 over lower cut-off values is that percentages obtained with the cut-off at 72 are less affected by differences between studies in the usage of a filter question that precedes the annoyance question.

4 Exposure – response model

The total dataset used to assess the exposure response relationships for a type of noise source has a hierarchical structure because the data come from different studies. Because methodological and other differences between studies affect the exposure response relationship, it is important to include 'study' as a variable in the exposure response model. This could be done by incorporating a dummy variable in the model for all (but one) studies. However, this would add many parameters to the model (one for each but one study), and separate exposure response relationships per study would be found instead of a synthesis curve.
A more informative result is obtained with less parameters, if the available studies are treated as a sample from all possible exposure response studies. Then, on the basis of this sample of studies, the exposure response relationship is established that gives the best single representation of all the curves that would be obtained with different study types. The following simple model is based on this idea and incorporates a random, normally distributed, effect of 'study':

$$y_{ij} = \beta_0 + \beta_1 \, DNL_{ij} + u_{1j} \, DNL_{ij} + e_{ij}$$

where y_{ij} is the response and DNL_{ij} the value of the exposure for the ith respondent in the jth study. The intercept coefficient β_0 is assumed to be the same at all studies, while the random variable u_{1j} represents the departure of the jth study's slope from the average slope β_1. The random variable u_{1j} is normally distributed with zero mean. The relationship $y_{ij} = \beta_0 + \beta_1 \, DNL_{ij}$ is the overall exposure response relationship that gives the best single representation of all the curves that would be obtained with different study types.
The above linear model is used for the relationships DNL – A because these relationships were earlier found to be linear (Miedema, 1992). A model extended with a quadratic term with a fixed and a random parameter is used for the relationship DNL - %HA, because this relationship is known to be quadratic (Miedema, 1992; Miedema and Vos, 1998).

The above model is called a multilevel model because it takes into account the effect of the clustering of data (in studies) (Goldstein, 1995). If the random study effect on the slope, i.e. the term $u_{1j} \, DNL_{ij}$, would be dropped from the model, a simple linear regression model would result. The parameters in such a simple regression model depend stronger on the studies with a large number of cases than the parameters in the multilevel model. Consequently, the outcome of the simple regression model better represents the curves found with the specific features of the large studies than the curves found with the specific features of the small studies. Moreover, the (wider) confidence intervals obtained with multilevel model are more accurate because the model takes into account the dependency among the observations within a single study.

The parameters of the models, and the mean and standard deviation of the distributions were estimated using the procedure MIXED with method MIVQUE0 in the SAS package (SAS Institute Inc, 1996).

5 DNL - %HA and DNL – A relationships

Synthesis curves for aircraft, road traffic, and railway are determined by fitting a quadratic multilevel model to the datapoints. Each point was weighted according to the number of observations on which it is based. Extreme exposure levels (< 45 and > 75 dB) were excluded from this analysis. It turned out that the three curves reached %HA = 0 at about DNL = 42 dB. Therefore a new analysis was conducted in which the curves were forced through zero at 42 dB (by dropping the intercept parameter β_0 from the model and replacing DNL by DNL - 42). The equations of the curves shown in figure 1 (new) are:

Aircraft: $\%HA = 0.07\,(DNL - 42) + 0.0510\,(DNL - 42)^2$

Road traffic: $\%HA = 0.08\,(DNL - 42) + 0.0360\,(DNL - 42)^2$

Rail: $\%HA = 0.37\,(DNL - 42) + 0.0062\,(DNL - 42)^2$

Figure 1(new sub) shows that the effect on the DNL - %HA curves caused by restricting the analysis to the datasets which have no asterix in table 1, is very small. The curves based on the total dataset for one source and the curve based on the datasets without asterix almost coincide. This means a curve found for DNL – A below, which necessarily is based on datasets without asterix, is the same as the curve that would have been found if all datasets could be used to establish the DNL – A curve.
Figure 1(jasa) also shows the DNL - %HA curves presented in Miedema and Vos (1998). The small differences with the curves based on all data found here are caused by the improvements in the dataset and, possibly, the usage of the MIVQUE0 method unstead of the (RE)ML method (see section 2).

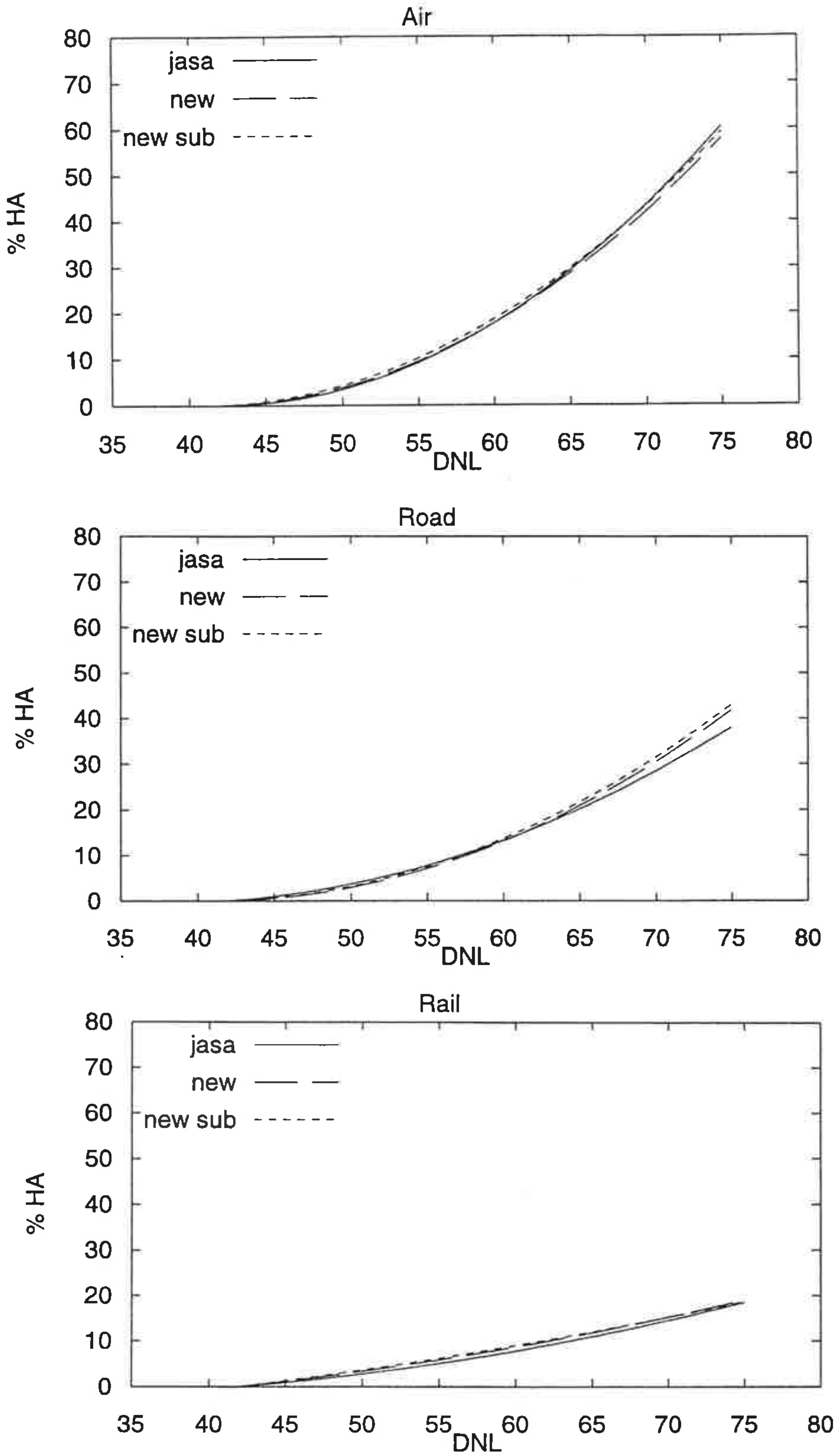

Figure 1: The DNL - %HA curves presented in Miedema and Vos (1998) (jasa), the curves obtained after the adaptions described in section 2 (new), and the curves after the adaption and based only on the datasets for which also the annoyance score A can be determined (new sub).

Figure 2 reproduces from figure 1 the curves for different types of sources based on all data found in one figure

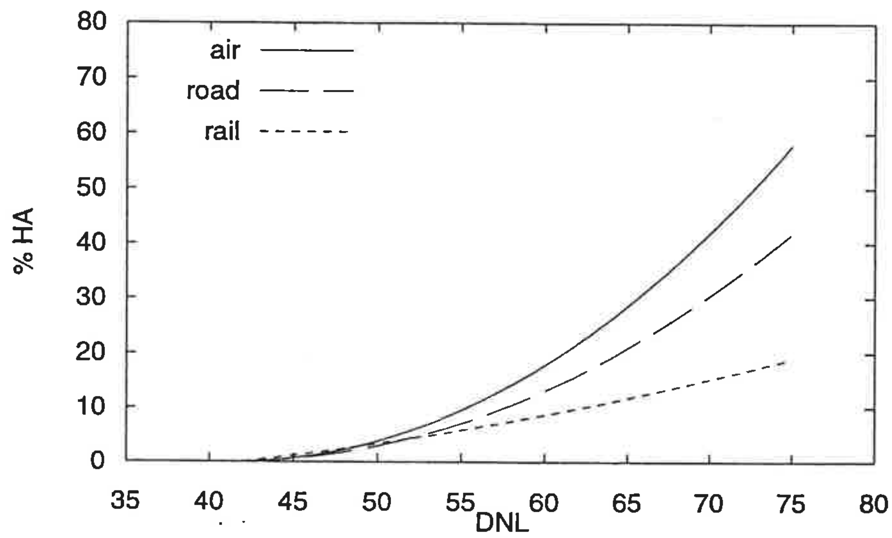

Figure 2: The DNL - %HA curves (the 'new' curves from figure 1)

To establish synthesis lines for the DNL – A relationships, a linear model was fitted. Figure 3 shows that the three lines reached A = 0 at about DNL = 37 dB. Therefore a new analysis was conducted in which the curves were forced through zero at 37 dB. The lines and the confidence intervals found are also shown in figure 4. The equations of the lines are:

Aircraft: $A = 1.83\,(DNL - 37)$

Road traffic: $A = 1.55\,(DNL - 37)$

Rail: $A = 1.19\,(DNL - 37)$

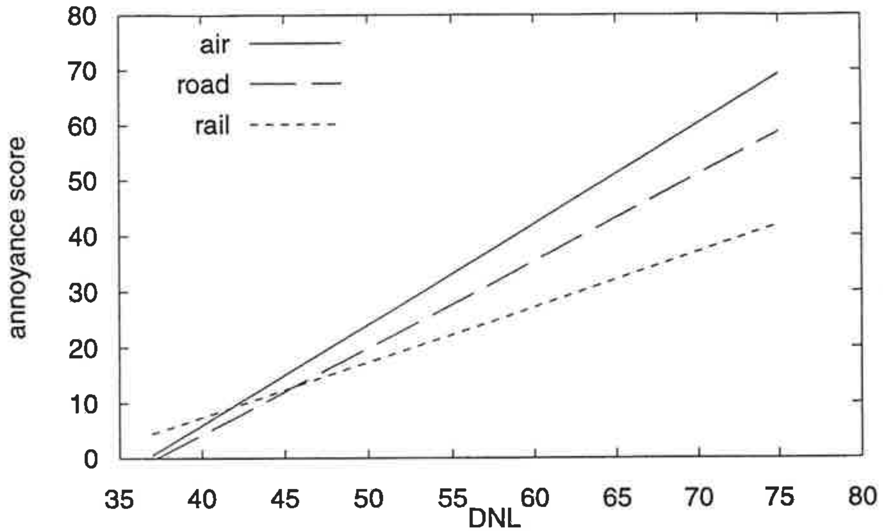

Figure 3: The DNL-A relationships

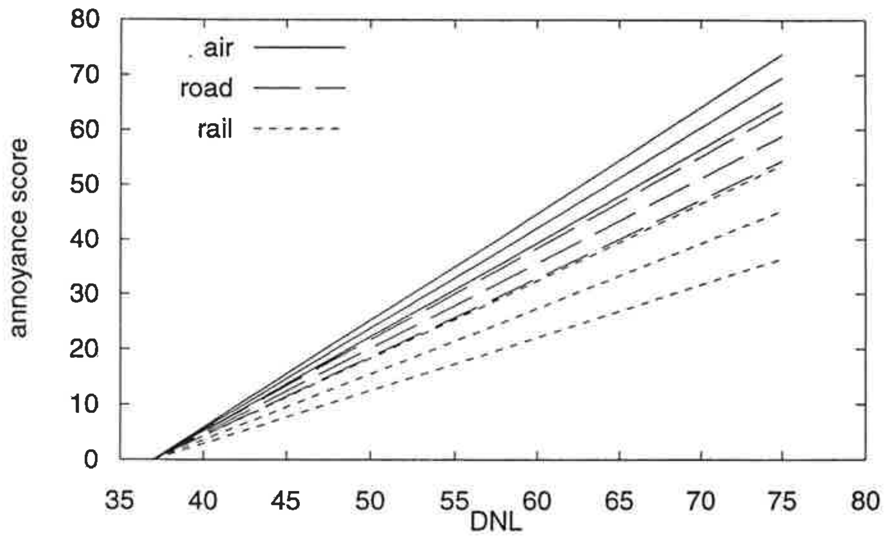

Figure 4: The DNL - A lines forced through A = 0 at DNL = 37 dB, with the 95% confidence intervals.

6 Stationary sources

Most environmental noise exposures are caused by transportation. There are, however, a wide variety of non-impulsive stationary sources (refinery, windmill park, air conditioning/chilling installations, ventilators, etc.). Non-impulsive stationary sources constitute a very heterogeneous category of noise sources. Moreover, incidents may contribute disproportional the noise annoyance caused by these sources. Therefore, it is not possible to find general relationships between a single noise metric such as DNL and an annoyance measure such as the annoyance score A which are as representative for this category of sources as the above relationships are for the transportation sources. The lack of data regarding non-impulsive stationary noise sources adds to the uncertainty about the community reaction to noise from these sources.
Miedema (1992) presented DNL – A curves for non-impulsive stationary sources. We are not aware of new data relevant for such curves that has been published since that time. Even though the uncertainty about these curves is large, we refer to them as the best available curves. The Working Group on noise indicators of the EU/DGXI noted in its position paper (EU/DGXI WG1, 1999) the lack of data on effects of industrial noise. The working group recommends that work is done to increase our knowledge on this point.

Specific aspects of the noise may contribute to the annoyance caused. Important aspects are impulsiveness ((un)loading, hammering at a shipyard, sorting of metal at a scrap yard, shunting yards, shooting ranges, etc.), tonality (air conditioning, squealing of a tram or train in a tight curve, etc) , and a relatively strong low-frequency component (artillery, underground). These characteristics are found predominantly for noise from stationary sources, but not exclusively. A procedure to account for these specific aspects may be developed in the following steps:

1. A procedure is defined for identifying whether an aspect (impulsiveness, tonality, strong low frequency component) is present or not, possibly distinguishing different levels.
2. A system of penalties is defined. These may be penalties that are defined in an all or none manner or the level of the penalty may depend on the level of impulsiveness, tonality, or low frequency component.
3. The penalty is applied to the LAeq in the period in which impulsiveness, tonality, or low frequency component occurs.
4. LAeq's are combined in the usual manner e.g. into DNL.
5. Annoyance is estimated with the proper curve (aircraft, road traffic, railway, or stationary sources) on the basis of the DNL (with penalties)

For further discussion of this topic we refer to, e.g., the position paper of the Working Group on noise indicators of the EU/DGXI (EU/DGXI WG1, 1999)

7 Conclusion

The annoyance score (A) increases as a function of DNL. Different lines were found for aircraft, road traffic, and railway noise. The rate of increase is higher for aircraft noise than for road traffic noise, which in turn has a higher rate of increase than railway noise. The 95 % confidence intervals around the different lines are mutually exclusive on a large range of the exposure levels. All lines converge at low DNL to A = 0 at circa 37 dB(A).
Curves for non-impulsive stationary sources are available, but the uncertainty about these curves is large. A procedure to account for specific aspects (impulsiveness, tonality, or a strong low frequency component) has been outlined.

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